Spécialité Systèmes Automatisés et Génie Informatique

Lock-in detection for Illuminance measurement

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ABSTRACT

This project proposes the design and implementation of an artificial luminosity measurement system in daylight conditions using lock-in detection.

In the context of the LARIS laboratory and the ROMULUX project, a robot has been developed that can map its environment and take luminosity measurements. However, due to the lack of control over lighting in buildings constructed according to standard norms, over-illumination tends to occur, leading to health issues, excessive energy consumption, and additional installation costs. The difficulty of effectively measuring artificial light during the day has motivated this project, which aims to enhance the capabilities of the light detector by using synchronous detection to discriminate artificial light from the "noise" of natural light. This will allow measurements to be taken during the day, thus avoiding the need to operate during unusual hours or obtain special authorizations to operate at night.

The project involves an analog part using a photodiode and amplification, followed by the implementation of lock-in detection using the AD630 analog demodulator. This technical solution offers an innovative approach to addressing the challenges associated with accurately measuring artificial luminosity in daylight environments, with significant implications for energy efficiency and human well-being.

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KEYWORDS

Lock-in detection, photodiode, PCB (Printed Circuit Board), amplifier, signal-to-noise ratio, Electromagnetic compatibility (EMC), light measurement, noise reduction, analog signal processing, and frequency modulation, synchronous detection.

INDEX

ABSTRACT 2

ACKNOWLEDGMENTS 2

KEYWORDS 2

INDEX OF FIGURES 5

INDEX OF TABLES 6

INDEX OF EQUATIONS 6

1. INTRODUCTION 7

  1.1 CONTEXT OF THE PROBLEM 7

  1.2 OBJECTIVES OF THE PROJECT 7

  1.3 STRUCTURE OF THE REPORT 7

2. THEORETICAL FRAMEWORK 9

  2.1 SIGNAL THEORY 9

    2.1.1 BASIC PRINCIPLES OF SIGNALS 9

    2.1.2 NOISE SOURCES AND SIGNAL-TO-NOISE RATIO 14

  2.2 LOCK-IN TECNCHNOLOGY AND SYNCHRONOUS DETECTION 16

    2.2.1 SYNCHRONOUS DETECTION 17

    2.2.2 PRINCIPLE OF OPERATION OF THE LOCK-IN AMPLIFIER 18

    2.2.3 MATHEMATICAL EXPLANATION 19

    2.2.4 LOCK-IN LIMITATIONS 21

    2.2.5 APPLICATIONS AND ADVANTAGES OF LOCK-IN TECHNOLOGY 22

  2.3 LIGHT MEASUREMENT METHODS 23

    2.3.1 PHOTOMETRIC VS RADIOMETRIC METHODS 23

    2.3.2 COMPARISON OF METHODS 24

  2.4 PHOTODIODES 25

    2.4.1 PRINCIPE OF OPERATION 25

    2.4.2 TYPES AND CHARACTERISTICS 27

    2.4.3 SELECTION CRITERIA 27

3. CIRCUIT DESIGN AND DEVELOPMENT 29

  3.1 CIRCUIT DESCRIPTION 29

    3.1.1 CIRCUIT SCHEMATIC 29

    3.1.2 DESCRIPTION OF COMPONENTS AND THEIR FUNCTION 29

  3.2 DESIGN PROCESS 32

    3.2.1 DESIGN CONSIDERATIONS 32

3.2.2 JUSTIFICATION OF DESIGN DECISIONS 33

4. PCB DEVELOPMENT 35

4.1 DESIGN AND MANUFACTURING PROCESS 35

4.1.1 TOOLS AND SOFTWARE USED 35

4.1.2 PCB DESIGN 35

4.1.3 PCB LAYOUT AND DESIGN VISUALIZATION 37

4.1.4 PCB ASSEMBLY PROCESS 39

4.1.5 PROPER ROUTING PRACTICES 41

4.2 ASSEMBLY AND SOLDERING 43

4.2.1 ASSEMBLY TECHNIQUES 43

4.2.2 PRECAUTIONS AND BEST PRACTICES 44

5. ELECTROMAGNETIC COMPATIBILITY (EMC) 46

5.1 EMC IN PCB DESIGN 46

5.1.1 IMPORTANCE OF EMC 46

5.1.2 DESIGN CONSIDERATIONS FOR EMC 47

5.2 EMI SOURCES AND MIGRATION TECHNIQUES 47

5.2.1 EMI SOURCES 47

5.2.2 MITIGATION TECHNIQUES 48

6. RESULTS ANALYSIS 50

6.1 PRESENTATION OF RESULTS 50

6.1.1 DATA OBTAINED 50

6.2 DISSCUSION OF RESULTS 55

6.2.1 COMPARISON WITH OTHER METHODS: BOXCAR AVERAGER 55

6.2.2 QUALITATIVE ANALYSIS OF RESULTS 58

7. PRACTICAL APPLICATIONS 59

7.1 EXAMPLES OF APPLICATIONS 59

7.1.1 INDUSTRIAL APPLICATIONS 59

7.1.2 SCIENTIFIC APPLICATIONS 59

7.2 BENEFITS AND LIMITATIONS 59

7.2.1 COMPARISON WITH OTHER MEASUREMENT METHODS 59

7.2.2 POTENTIAL IMPROVEMENTS 60

8. CONCLUSIONS 61

8.1 SUMMARY OF RESULTS 61

8.2 ACHIEVEMENTS 61

8.3 FUTURE RESEARCH DIRECTIONS 61
REFERENCES 63
CITED SOURCES 63
CONSULTED SOURCES 64
Annex A: Circuit Schematic Diagram 67

INDEX OF FIGURES

Figure 1. Analog signal. (Analog vs. Digital Signals: Uses, Advantages and Disadvantages | Article | MPS, n.d.) 9
Figure 2. Digital signal. (Analog vs. Digital Signals: Uses, Advantages and Disadvantages | Article | MPS, n.d.) 9
Figure 3.Deterministic and random signals. (What Is a Signal , 2024) 10
Figure 4.Periodic and non-periodic signals. (Signals and Systems - Electronics Projects, n.d.) 10
Figure 5.Representation of properties of signals. (Figure 3.1, n.d.) 11
Figure 6. Visual example of signal with noise. (All About Signal to Noise Ratio - Hollyland, 2023 .. 14
Figure 7. Synchronous detector. 17
Figure 8. Lock-in working principle. (*Principles of Lock-in Detection | Zurich Instruments*, 2019) .. 18
Figure 10. Schematic of the lock-in amplification. (Principles of Lock-in Detection | Zurich Instruments, 2019) 19
Figure 9.Reference signal used in the prototype of the project circuit. 19
Figure 11.Photodiode symbol. (Fichier, n.d.) 25
Figure 12. P-N Photodiode Cross-section. (PHOTODIODE BASICS – Wavelength Electronics, n.d.). 26
Figure 13. I-V characteristic of a photodiode. (‘Photodiode’, 2024). 26
Figure 14.Photodiode stage. 30
Figure 15. Amplifier stage x10. 30
Figure 16. Reference signal stage. 31
Figure 17. AD630 Configured as a Gain-of-One Balanced Modulator 31
Figure 18. Low pass filters. (Active right, passive left) 32
Figure 19. PCB schematic. 36
Figure 20. PCB Layout with Circuit Elements. 37
Figure 21. PCB layout with Labelled Stages 37
Figure 22. PCB layout with labelled stages and test pads. 38
Figure 23. ProtoMat S63 Milling Machine 39
Figure 24. Initial PCB layout on ProtoMat S63. 39
Figure 25. Photo taken during the milling. 40
Figure 26.Finished PCB without components. 40
Figure 27. Finished PCB with components. 40
Figure 28.Keep minimum distance and segment length at bends. (Shashikanth, 2020) 41
Figure 29. Increasing the space between traces to prevent crosstalk. (Shashikanth, 2020) 42
Figure 30. Route vias in a grid pattern to avoid hotspots. (Shashikanth, 2020) 42
Figure 31. Photodiode stage 50

Figure 32. x10 amplifier stage 51
Figure 33. X100 + HPF stage. 52
Figure 34. x10 amplification stage. 53
Figure 35. Summing stage. 53
Figure 36. Inverting stage. 54
Figure 37. Lock-in amplifier and LPF stage. 55
Figure 38. Boxcar Averager schematic. (Principles of Boxcar Averaging | Zurich Instruments, 2022) 56
Figure 39. Working principle of a boxcar averager. (Principles of Boxcar Averaging | Zurich Instruments, 2022). 57

INDEX OF TABLES

Table 1. Signal data in the photodiode stage. 50
Table 2. Signal data in the x10 amplification stage. 51
Table 3. Signal data in the x100 amplification + HPF stage. 51
Table 4. Signal data in the x10 amplification of the reference stage. 52
Table 5. Signal data in the summing stage. 53
Table 6. Signal data in the inverting stage. 53
Table 7. Signal data in the lock-in amplifier and LPF stage. 54

INDEX OF EQUATIONS

Equation 1. Complex signal. 10
Equation 2. Signal-to-noise ratio. 15
Equation 3. Synchronous detection signal. 17
Equation 4. Imput signal. 19
Equation 5. Reference Signal. 20
Equation 6.Multiplication of Imput and Reference Signals. 20
Equation 7. Expanded Product. 20
Equation 8. Trigonometric Expansion. 20
Equation 9. Low-Pass Filtered Output. 20
Equation 10. Multiplication with Sine Reference. 20
Equation 11. Expanded Product with Sine Reference. 20
Equation 12. Low-Pass Filtered Output with Sine Reference. 21
Equation 13. In-Phase Component (I) 21
Equation 14. Quadrature component (Q). 21
Equation 15. Amplitude Calculation. 21
Equation 16. Phase Calculation. 21

1. INTRODUCTION

1.1 CONTEXT OF THE PROBLEM

In the LARIS laboratory, a robot has been designed through the ROMULUX project, capable of both mapping its environment and conducting luminosity measurements. The context of this project is that buildings are constructed to comply with lighting standards, which in practice are rarely monitored. To ensure these standards are met, over-lighting is often practiced, leading to several consequences including adverse effects on health (visual comfort), increased energy consumption (overconsumption), higher installation costs (more lighting installed), and more.

Lighting control is rarely performed because it is very difficult to carry out manually. In this context, the use of a robot becomes an interesting solution, and it is for this reason that the robotics team designed ROMULUX. By definition, if we measure artificial light, it is appropriate to make these measurements at night to avoid natural light interference, especially when these measurements concern outdoor installations. However, operating at night on certain sites often requires specific authorizations, and it is relatively inconvenient for the operator to work during odd hours.

1.2 OBJECTIVES OF THE PROJECT

This project aims to enhance the capabilities of the light detector using synchronous detection to discriminate only artificial light within the "noise" of natural light, thus allowing operation during the day. To achieve this, a PCB has been designed incorporating a photodiode and a lock-in amplifier to quantify the amount of artificial light present without being affected by natural light exposure.

1.3 STRUCTURE OF THE REPORT

The report is structured as follows:

Theoretical Framework: This section provides the foundational knowledge required to understand the project. It begins with an overview of signal theory, explaining basic principles such as types of signals, their properties, and the concept of noise in signal processing. A detailed explanation of lock-in technology follows, covering the principle of operation of the lock-in amplifier and its advantages in detecting weak signals buried in noise. This section also includes a comparison between different light measurement methods, focusing on photometric and radiometric techniques, and discusses the rationale for choosing a photodiode for this project. Finally, it examines the operation principles of photodiodes, the types available, and the criteria for selecting an appropriate photodiode for light measurement.

Signal Processing: This section explores various signal processing techniques relevant to the project, such as filtering, modulation, and demodulation. It explains how these techniques are used to manipulate signals to extract useful information and improve signal-to-noise ratio.

Circuit Design and Development: This section delves into the practical aspects of the project. It starts with a detailed description of the circuit, including a schematic and an explanation of each component's function. Then, it discusses the design process, highlighting the choices and decisions made, such as selecting components and determining the layout. Additionally, it covers the PCB development process, from design to manufacturing, and includes images of the PCB and the manufacturing process.

Electromagnetic Compatibility (EMC): This section addresses the principles of EMC and their importance in electronic design. It explains the basics of electromagnetic compatibility, common issues that can arise in electronic circuits, and the practical strategies and design tweaks implemented to enhance the PCB's EMC performance.

Results Analysis: This section presents and analyzes the data collected during the project. It includes tables and graphs of the measurements taken, and interprets the results by comparing them with expected outcomes and analyzing any discrepancies. It also includes a comparison with other light measurement methods and discusses the effectiveness of the implemented solutions.

Practical Applications: This section explores potential real-world uses for the improved light detection system. It provides detailed examples of applications in industrial and scientific settings, discusses the advantages of the system over traditional methods, and addresses any limitations or challenges encountered.

Conclusions: This section summarizes the project's findings and achievements. It recaps the key results and their significance, provides an overview of the main accomplishments, and suggests potential areas for further research and development based on the project's outcomes.

References: This section lists all the scholarly and technical references used throughout the report, adding credibility and allowing others to follow up on the work.

Appendices: This section includes additional material that supports the main content of the report.

2. THEORETICAL FRAMEWORK

2.1 SIGNAL THEORY

Signal theory is a fundamental aspect of electrical engineering and electronics, dealing with the analysis, interpretation, and manipulation of signals. A signal is any time-varying or spatial-varying quantity that carries information. Understanding signal theory is crucial for the design and analysis of systems that detect, process, and transmit signals (Oppenheim & Willsky, 1997).

2.1.1 BASIC PRINCIPLES OF SIGNALS

A signal is a function of one or more variables that indicate a (usually physical) phenomenon. The signal serves as a carrier of information between communication devices. They can transmit different types of information depending on the application required. These signals can be of different forms (*What Is a Signal,* 2024).

2.1.1.1 TYPES OF SIGNALS

There can be different types of signals:

Analog signals: These signals are continuous (e.g., a real variable) and vary infinitely with the time parameter or can take any value within a given range. These signals are represented by the sine wave. Examples of analog signals are audio signals, temperature readings, sound waves, or television waves.

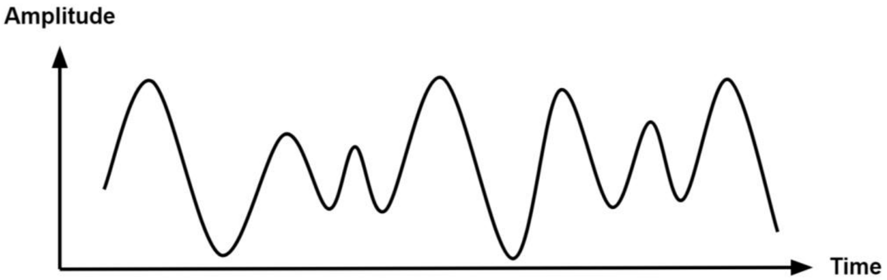

Figure 1. Analog signal. (Analog vs. Digital Signals: Uses, Advantages and Disadvantages | Article | MPS, n.d.)

Digital signals: A signal which is a function of discrete variables (for example, an integer variable) is said to have discrete time and this is represented in binary form (0 and 1). More robust against noise. Commonly used in computer systems and telecommunications.

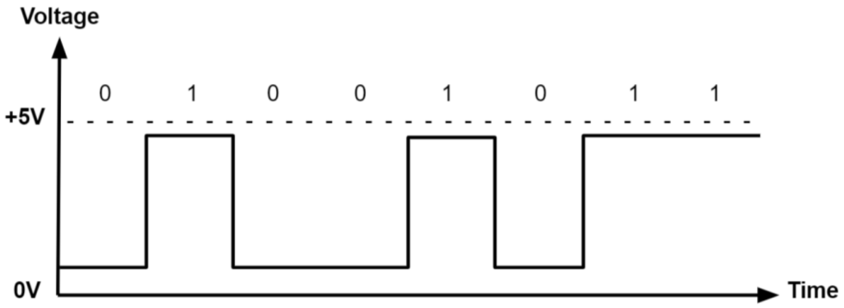

Figure 2. Digital signal. (Analog vs. Digital Signals: Uses, Advantages and Disadvantages | Article | MPS, n.d.)

Real and complex signals: If the value of the signal x(t) is a real number, the signal x(t) is also a real signal; If the value of the signal x(t) is a complex number, the signal x(t) is complex. signal. In general, the complex signal x(t) is a function of the form:

$$x(t) = x_1(t) + jx_2(t)$$

Equation 1. Complex signal.

Where x1(t) and x2(t) are real, and $j = \sqrt{-1}$

Deterministic and random signals: A deterministic signal is one whose value is always precisely specified. Therefore, the decision signal can be modelled by knowing the time t. A random signal takes a long time and must be characterized.

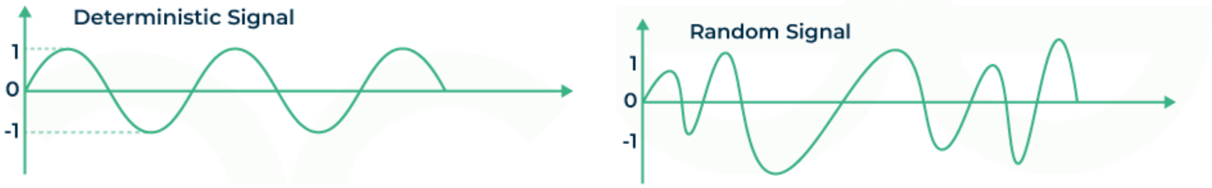

Figure 3.Deterministic and random signals. (What Is a Signal , 2024)

Periodic and non-periodic signals: A continuous signal is a signal of infinite duration that repeats the same pattern over and over again is called a periodic signal . One-sided or time-limited signals can never be periodic. Any continuous time signal that is not a periodic signal is called a nonperiodic (or aperiodic) signal.

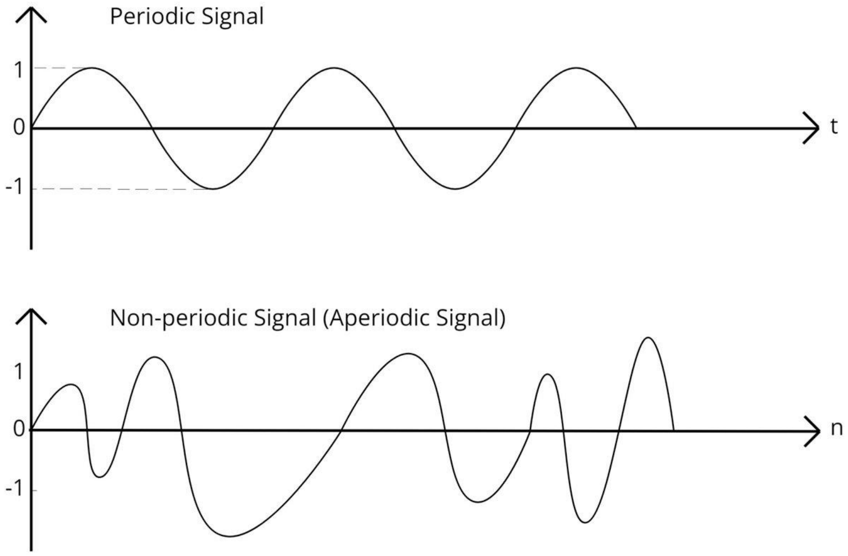

Figure 4.Periodic and non-periodic signals. (Signals and Systems - Electronics Projects, n.d.)

2.1.1.2 PROPERTIES OF SIGNALS

Some of the most important properties of signals are:

Amplitude: The maximum value of the signal.
Frequency: The rate at which the signal oscillates, measured in Hertz (Hz).
Phase: The position of the waveform relative to a reference point in time.
Wavelength: The distance over which the signal's shape repeats (for spatial signals).

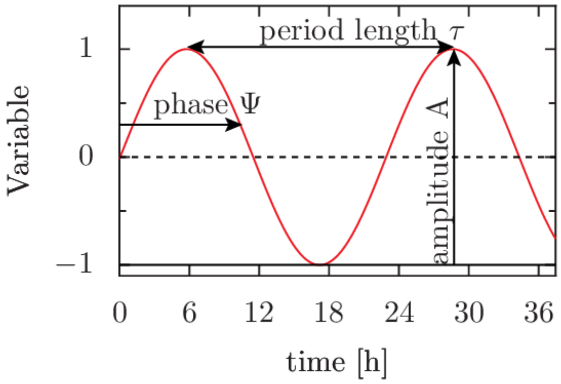

Figure 5.Representation of properties of signals. (Figure 3.1, n.d.)

2.1.1.3 SIGNAL REPRESENTATION

Signal representation is a fundamental aspect of signal processing, crucial for understanding and analyzing how signals behave and interact in different domains. Signals can be represented in various ways, with **time-domain** and **frequency-domain** representations being the most common.

In the **time-domain** representation, signals are analyzed as functions of time. This means that the signal is observed and interpreted as it varies over time. For example, if we consider the output of a photodiode detecting light, the time-domain signal would show how the light intensity changes over time. This type of representation is intuitive and directly related to the real-world phenomena being measured.

In this project, the photodiode converts light into an electrical signal, which can be captured and displayed as a voltage or current that varies over time. By examining the time-domain signal, you can observe the immediate response of the sensor to changes in light intensity, identify transient events, and monitor the overall behaviour of the light detection system. This is particularly useful for detecting fluctuations in light levels and understanding how quickly the system responds to changes in illumination.

The **frequency-domain** representation, on the other hand, analyzes signals based on their frequency components. This is typically achieved using mathematical transformations, such as the Fourier Transform, which decomposes a time-domain signal into its constituent frequencies. The resulting frequency-domain signal provides a spectrum that shows the amplitude and phase of each frequency component present in the original time-domain signal. This representation is particularly useful for understanding how different frequencies contribute to the overall signal, which is crucial in applications involving signal modulation, noise analysis, and filtering. In the context of your project, the frequency-domain analysis becomes essential when employing lock-in amplification.

Lock-in amplifiers operate by mixing the input signal with a reference signal at a specific frequency, thereby shifting the desired signal component to a new frequency while suppressing noise and other unwanted components. By analyzing the signal in the frequency domain, you can isolate and extract the artificial light signal from the ambient natural light and noise. This enables the system to accurately measure the intensity of artificial light even in the presence of varying levels of natural light.

For example, if the artificial light is modulated at a known frequency, the lock-in amplifier can be tuned to that frequency, allowing to selectively enhancing the signal of interest. The frequency-domain representation allows visualizing and quantifying how effectively the lock-in amplifier isolates the desired signal from noise and other interference.

Understanding both time-domain and frequency-domain representations is crucial for designing and optimizing the light detection system in your project. The time-domain analysis provides insights into the dynamic response and real-time behaviour of the photodiode sensor, while the frequency-domain analysis, facilitated by the lock-in amplifier, enables precise discrimination of artificial light signals from noise.

By leveraging these signal representation techniques, you can ensure that the light detection system operates reliably and accurately under varying environmental conditions, ultimately improving the robot's capability to perform luminosity measurements and adhere to lighting standards.

2.1.1.4 SIGNAL PROCCESSING

Signal processing encompasses a variety of techniques used to analyze, modify, and synthesize signals. These techniques are essential for improving the quality of signals, extracting useful information, and facilitating communication and measurement systems. In your project, signal processing plays a crucial role in enhancing the performance of the light detection system using a photodiode and a lock-in amplifier.

Filtering is the process of removing unwanted components from a signal, typically noise or other interference, to enhance the desired signal. There are several types of filters, including low-pass, high-pass, band-pass, and band-stop filters, each designed to allow certain frequencies to pass while attenuating others.

In the context of this project, filtering is particularly important because the photodiode sensor may pick up not only the desired artificial light but also various noise components, such as ambient natural light, electrical noise from the environment, and other electromagnetic interference. By implementing appropriate filters, you can isolate the frequency range of interest, which corresponds to the artificial light signal, and suppress unwanted noise.

For instance, if the artificial light is modulated at a specific frequency, a band-pass filter centred around that frequency can be used to enhance the signal of interest while rejecting frequencies outside this range. This ensures that the light detection system provides a clean and accurate measurement of the artificial light intensity.

Modulation is all about tweaking a signal to carry information. It’s a big deal in communication systems, where info gets sent through different channels. Modulation means changing stuff like the strength, speed, or shape of a main signal, depending on the info you’re sending.

In this case, we can use modulation on the artificial light source. By tweaking the artificial light at a set frequency, you make a unique signal that stands out from the background noise. This comes in handy when you’re trying to measure light in places with natural light and other distractions.

For instance, you can use tricks like amplitude modulation (AM) or frequency modulation (FM) to pack info into the artificial light signal. When the light detection system grabs this tweaked signal, its special pattern makes it easy to spot and measure, even when there’s lots of background noise.

Demodulation is the reverse process of modulation, where the original information is extracted from the modulated signal. Once the photodiode captures the modulated artificial light signal, the next step is to demodulate this signal to retrieve the underlying information about the light intensity.

Using a lock-in amplifier, the system can perform demodulation by mixing the captured signal with a reference signal that matches the modulation frequency. This process shifts the modulated signal to a lower frequency (or baseband), where it can be more easily analyzed and quantified. Demodulation helps to accurately recover the artificial light signal from the composite signal received by the photodiode, effectively filtering out the noise and other interference.

For instance, if the artificial light signal is frequency modulated, the lock-in amplifier can demodulate it by locking onto the specific frequency and extracting the amplitude variations that represent the light intensity. This enables precise measurements of the artificial light, independent of the ambient natural light levels.

Signal processing techniques, including filtering, modulation, and demodulation, are integral to the functionality and accuracy of the light detection system during the project. Filtering removes unwanted noise, modulation encodes the artificial light signal for distinct identification, and demodulation extracts the relevant information from the received signal. Together, these processes ensure that the system can operate effectively in diverse lighting conditions, providing reliable measurements of artificial light intensity for applications in building compliance and energy efficiency.

By understanding and applying these signal processing techniques, the performance of the light detection system can be enhanced, enabling it to discriminate between artificial and natural light and ensure accurate luminosity measurements.

2.1.2 NOISE SOURCES AND SIGNAL-TO-NOISE RATIO

In any signal processing system, understanding noise sources and managing the signal-to-noise ratio (SNR) is crucial for accurate measurement and analysis. Noise can significantly degrade the performance of a system, masking the desired signal and reducing its clarity. In the context of your project, which involves detecting artificial light using a photodiode and a lock-in amplifier, identifying and mitigating noise sources is essential for reliable operation.

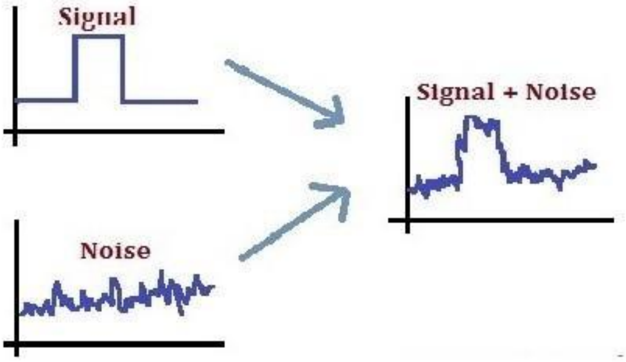

Figure 6. Visual example of signal with noise. (All About Signal to Noise Ratio - Hollyland, 2023

Noise in electronic and optical systems can originate from various sources. Understanding these sources helps in designing effective strategies to minimize their impact:

1. **Thermal Noise:**
    - **Origin:** generated by the thermal agitation of the electrons inside an electrical conductor at equilibrium. (*NF Corporation*, n.d.).
    - **Characteristics:** Also known as Johnson or Nyquist noise, it is present in all resistive components and is proportional to temperature. (*NF Corporation*, n.d.).
    - **Impact on project:** Thermal noise can affect the photodiode and other electronic components, introducing a baseline level of noise that can obscure weak light signals.

2. **Shot Noise:**
    - **Origin**: Shot noise also occurs in photon counting in optical devices, where shot noise is associated with the particle nature of light. (‘Shot Noise’, 2024).
    - **Characteristics:** Shot noise is inherent to all semiconductor devices and is proportional to the current flowing through the device. (‘Shot Noise’, 2024).
    - **Impact on project:** Shot noise affects the photodiode's output signal, particularly under low light conditions where the photocurrent is small.

3. **Flicker Noise:**
    - **Origin:** also called *1/f noise*. Its origin is one of the oldest unsolved problems in physics. It is pervasive in nature and in many human endeavors. It is present in all active and many passive devices. It may be related to imperfections in crystalline structure of semiconductors, as better processing can reduce it. (*Flicker Noise - an Overview | ScienceDirect Topics*, n.d.).
    - **Characteristics:** It has a higher magnitude at lower frequencies and decreases with increasing frequency. (*Flicker Noise - an Overview | ScienceDirect Topics*, n.d.).
    - **Impact on project:** Flicker noise can impact low-frequency signal components, complicating the detection of slowly varying light signals.

4. **Environmental Noise:**
    - **Origin:** External electromagnetic interference (EMI) from sources such as power lines, radio transmitters, and other electronic devices. (‘Environmental Noise’, 2024).
    - **Characteristics:** Environmental noise can be broad-spectrum and vary in intensity and frequency. (‘Environmental Noise’, 2024).
    - **Impact on Your Project:** EMI can couple into the photodiode circuit and other parts of the measurement system, introducing noise that can interfere with signal detection.

5. **Optical Noise:**
    - **Origin:** Variations in ambient light, such as sunlight, reflections, and stray light from artificial sources. (*Optical Noise Source (NOISE) - INTERCONNECT Element*, n.d.).
    - **Characteristics:** Optical noise fluctuates with changes in the environment and can be both random and periodic. (*Optical Noise Source (NOISE) - INTERCONNECT Element*, n.d.).
    - **Impact on project:** Ambient light variations can interfere with the photodiode's ability to accurately measure the artificial light signal.

In terms of definition, SNR or signal-to-noise ratio is the ratio between the desired information or the power of a signal and the undesired signal or the power of the background noise.

Also, SNR is a measurement parameter in use in the fields of science and engineering that compares the level of the desired signal to the level of background noise. In other words, SNR is the ratio of signal power to the noise power, and its unit of expression is typically decibels (dB). Also, a ratio greater than 0 dB or higher than 1:1, signifies more signal than noise. (What Is Signal to Noise Ratio and How to Calculate It, 2022).

$$\mathrm{SNR\ (dB)} = 10\log_{10}\frac{\mathrm{Pnoise}}{\mathrm{Psignal}}$$

Equation 2. Signal-to-noise ratio.

Where:

- P_{signal} is the power of the desired signal.
- P_{noise} is the power of the noise.

A high SNR indicates a clear and distinguishable signal, while a low SNR implies that noise is significantly affecting the signal. In your project, achieving a high SNR is crucial for accurately detecting and measuring the artificial light signal. The lock-in amplifier plays a vital role in enhancing the SNR by selectively amplifying the signal at the modulation frequency of the artificial light and rejecting noise at other frequencies.

Strategies to Improve SNR

1. **Modulation and Lock-In Detection:**
    - Modulate the artificial light at a specific frequency and use a lock-in amplifier to demodulate the signal. This technique shifts the signal to a higher frequency where noise is lower and allows for selective amplification.

2. **Filtering:**
    - Use band-pass filters to isolate the signal frequency and reject out-of-band noise, including environmental and thermal noise.

3. **Shielding and Grounding:**
    - Implement proper electromagnetic shielding and grounding techniques to reduce EMI coupling into the circuit.

4. **Optimizing Component Selection:**
    - Choose low-noise components, such as low-noise amplifiers and precision resistors, to minimize the introduction of additional noise into the system.

5. **Temperature Control:**
    - Maintain a stable temperature environment for the photodiode and other sensitive components to reduce thermal noise.

By understanding and addressing noise sources, and employing techniques to improve the SNR, you can enhance the accuracy and reliability of the light detection system. This ensures that the measurements of artificial light are precise, even in the presence of varying environmental conditions and noise sources.

2.2 LOCK-IN TECNCHNOLOGY AND SYNCHRONOUS DETECTION

This subsection provides a detailed explanation of lock-in technology, covering the principle of operation of the lock-in amplifier and its advantages in detecting weak signals buried in noise. Here, the concept of synchronous detection is introduced as a critical technique used by lock-in amplifiers to improve the signal-to-noise ratio.

2.2.1 SYNCHRONOUS DETECTION

In electronics, a synchronous detector is a device that recovers information from a modulated signal by mixing the signal with a replica of the unmodulated carrier. This can be locally generated at the receiver using a phase-locked loop or other techniques. Synchronous detection preserves any phase information originally present in the modulating signal. For example, with the exception of SECAM receivers, synchronous detection is a necessary component of any analog colour television receiver, where it allows recovery of the phase information that conveys hue. Synchronous detectors are also found in some shortwave radio receivers used for audio signals, where they provide better performance on signals that may be affected by fading. (‘Synchronous Detector’, 2023)

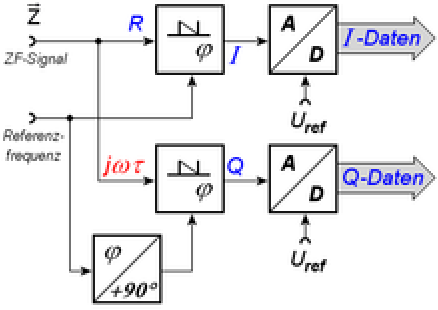

Figure 7. Synchronous detector.

Mathematically, this process can be described as:

$$\mathrm{Vout(t)} = \mathrm{Vin(t)} \cdot cos(\mathrm{\omega t})$$

Equation 3. Synchronous detection signal.

Where Vin(t) is the input signal and cos(ωt) is the reference signal. After low-pass filtering, the output voltage Vout(t) represents the amplitude of the input signal at the reference frequency.

2.2.2.1 ADVANTAGES OF SYNCHRONOUS DETECTION

Two of the most important advantages of synchronous detection are:

1. **Noise Reduction:** By focusing on a specific frequency, synchronous detection effectively reduces the impact of noise outside the frequency band of interest.

2. **Enhanced Sensitivity:** This method allows for the detection of signals that are much weaker than the noise level, making it ideal for applications requiring high sensitivity.

2.2.2.2 APPLICATION IN PHOTODIODE-BASED LIGHT MEASUREMENT

The implementation of synchronous detection in a photodiode-based light measurement system ensures that even weak light signals can be accurately measured despite the presence of substantial background noise. This is particularly valuable in environments where light signals are weak and prone to interference.

By integrating synchronous detection into the lock-in amplifier, the system can achieve precise and reliable measurements, which is crucial for the accurate quantification of light in various applications.

2.2.2 PRINCIPLE OF OPERATION OF THE LOCK-IN AMPLIFIER

Lock-in detection is a technique for the detection of the amplitude and phase of a sinusoidal signal with a known frequency. Its distinctive advantage over other detection techniques is that it can selectively determine the amplitude and phase of a signal at just the desired frequency (within a narrow band), and reject signals with other frequencies. This significantly boosts the signal to noise ratio of the detection system. (Lock-in detection, n.d).

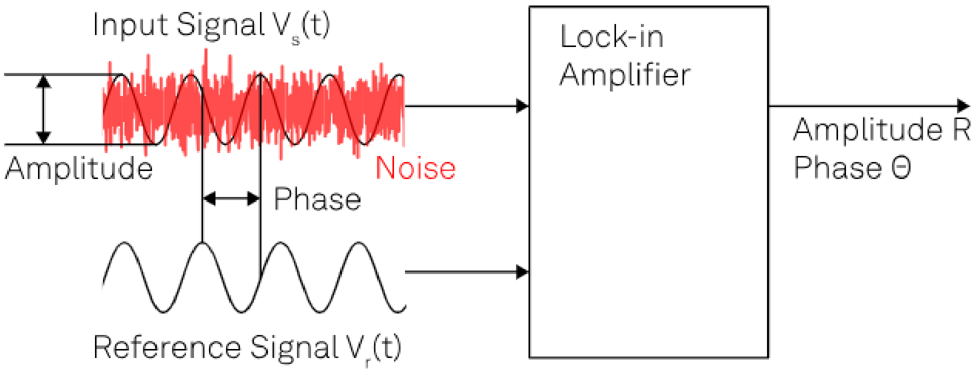

Figure 8. Lock-in working principle. (*Principles of Lock-in Detection | Zurich Instruments*, 2019)

These amplifiers are capable of extracting a signal from a highly noisy environment (See figure 7) using this periodic signal and its time dependency. They perform a multiplication of the periodic signal with the reference signal and apply a low-pass filter to the result. This method is called demodulation or phase-sensitive detection and isolates the signal at the frequency of interest from all other frequency components. The reference signal can be generated by the lock-in amplifier itself or provided to the amplifier by an external source. (Lock-in Amplifiers | Zurich Instruments, 2019). In our case, we will use the same signal we want to measure to create our own reference signal, to ensure that we obtain a reference signal with the same phase.

The reference signal is usually a sinusoidal signal, but it can have other forms, as in our case, where we will be using a square wave signal (see Figure 6) due to the limitations imposed by the circuit when generating our reference signal.

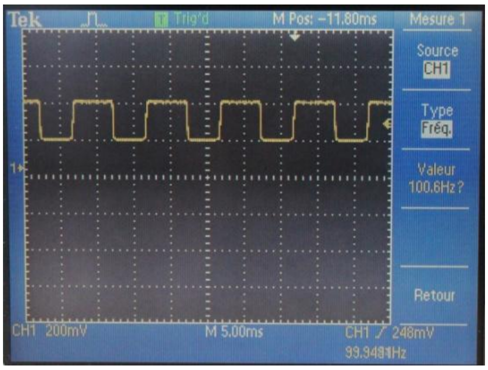

Figure 9.Reference signal used in the prototype of the project circuit.

Lock-in amplification use **synchronous detection** to isolate and amplify the signal of interest. The high precision and sensitivity of lock-in amplifiers is illustrated though a detailed mathematical explanation below, aiming to explain how indispensable tools are in various scientific and industrial applications.

2.2.3 MATHEMATICAL EXPLANATION

Lock-in amplification leverages the concept of synchronous detection, where the signal of interest is modulated and then demodulated using a reference signal. This process significantly enhances the signal-to-noise ratio (SNR) by filtering out noise components that are not at the reference frequency.

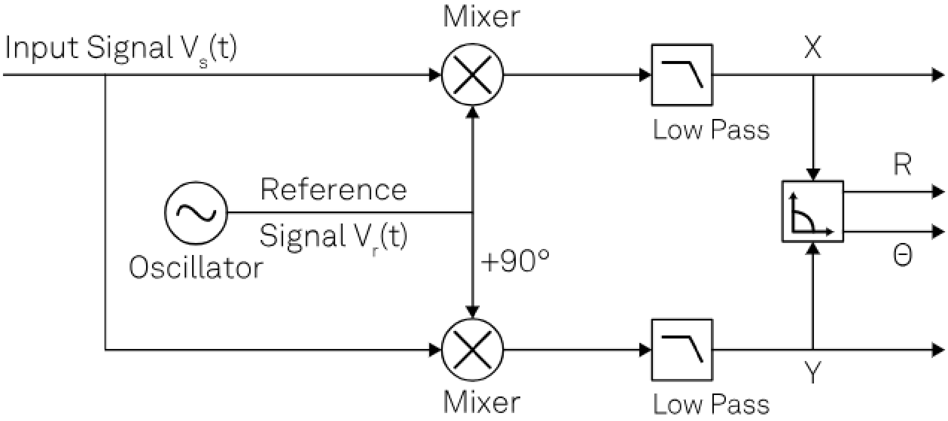

Figure 10. Schematic of the lock-in amplification. (Principles of Lock-in Detection | Zurich Instruments, 2019)

Signal modulation: consider an imput signal Vs(t) composed of a small signal of interest and noise:

$$\mathrm{Vs}(t) = \mathrm{A}\cos(\omega t + \phi) + \mathrm{N}(t)$$

Equation 4. Imput signal.

Where:

- A is the amplitude of the signal of interest.
- ω is the angular frequency of the signal.
- ϕ is the phase of the signal.
- N(t) is the noise component.

Reference Signal: A reference signal Vr(t) with the same frequency as the signal of interest is generated:

$$\mathrm{Vr(t)} = \cos(\omega t)$$

Equation 5. Reference Signal.

Multiplication (Mixing): The input signal Vsig(t) is multiplied by the reference signal Vref(t)

$$\mathrm{Vmult(t)} = \mathrm{Vs(t)} \cdot \mathrm{Vr(t)} = [A cos(\omega t + \phi) + \mathrm{N(t)}] cos(\omega t)$$

Equation 6.Multiplication of Imput and Reference Signals.

Using trigonometric identities, this product can be expanded as:

$$\mathrm{Vmult(t)} = \mathrm{A}\cos(\omega t + \phi)\cos(\omega t) + \mathrm{N(t)}\cos(\omega t)$$

Equation 7. Expanded Product.

$$\mathrm{Vmult(t)} = \frac{\mathrm{A}}{2}[\cos(\phi) + \cos(2\omega t + \phi)] + \mathrm{N(t)}\cos(\omega t)$$

Equation 8. Trigonometric Expansion.

Low-Pass Filtering: The product Vmult(t) contains a DC component $\frac{A}{2}\cos(\phi)$, a high-frequency component $\frac{A}{2}\cos(2\omega t+\phi)$, and a noise term. By passing this signal through a low-pass filter, the high-frequency component and most of the noise can be removed:

$$\mathrm{VLPF(t)} = \frac{\mathrm{A}}{2}\cos(\phi)$$

Equation 9. Low-Pass Filtered Output.

Phase Sensitivity: To make the lock-in amplifier phase-sensitive, a second reference signal sin(ωt) is used to multiply the input signal:

$$\mathrm{Vmult'(t)} = \mathrm{Vsig(t)} \cdot sin(\omega t) = [A cos(\omega t + \phi) + \mathrm{N(t)}] sin(\omega t)$$

Equation 10. Multiplication with Sine Reference.

$$\mathrm{Vmult'(t)} = 2\mathrm{A}[\sin(\phi) + \sin(2\omega t + \phi)] + \mathrm{N(t)}\sin(\omega t)$$

Equation 11. Expanded Product with Sine Reference.

After low-pass filtering:

$$\mathrm{VLPF}'(\mathrm{t}) = \frac{\mathrm{A}}{2}\sin(\phi)$$

Equation 12. Low-Pass Filtered Output with Sine Reference.

Quadrature Detection: The outputs VLPF(t) and VLPF’(t) are the in-phase (I) and quadrature (Q) components of the signal:

$$\mathrm{I} = \frac{\mathrm{A}}{2}\cos(\phi)$$

Equation 13. In-Phase Component (I)

$$\mathrm{Q} = \frac{\mathrm{A}}{2}\sin(\phi)$$

Equation 14. Quadrature component (Q).

The amplitude A and phase ϕ of the signal can be determined from these components:

$$\mathrm{A} = \sqrt{\mathrm{I}^2 + \mathrm{Q}^2}$$

Equation 15. Amplitude Calculation.

$$\emptyset = \tan\left(\frac{Q}{I}\right)^{-1}$$

Equation 16. Phase Calculation.

The lock-in amplifier effectively isolates the signal of interest from a noisy background by multiplying the input signal with a reference signal and applying a low-pass filter to extract the desired signal component. This technique is highly advantageous for measurements in noisy environments and is widely used in various scientific and industrial applications.

2.2.4 LOCK-IN LIMITATIONS

As with all electronic devices, lock-in amplifiers are not without their limitations. Despite their effectiveness in extracting signals from noisy environments, several factors can affect their performance and practicality. Understanding these limitations is crucial for optimizing their use and ensuring accurate measurements.

Signal-to-Noise Ratio (SNR) Limits: Lock-in amplifiers are highly effective at extracting signals from noise, but if the signal is too weak relative to the noise, the method may still struggle. Extremely low SNR can lead to inaccurate measurements or failure to detect the signal altogether.

Frequency Constraints: The lock-in detection method relies on the reference signal frequency. If the signal of interest and the noise have overlapping frequencies or if the signal frequency varies significantly, it can be challenging to isolate the desired signal.

Phase Sensitivity: Accurate phase matching between the reference and the signal is critical. Any phase error can affect the amplitude measurement and introduce inaccuracies.

Complexity and Cost: Lock-in amplifiers, especially those with high precision and advanced features, can be complex to design and operate. This complexity often translates to higher costs for equipment and maintenance.

Latency: Lock-in amplifiers may introduce latency due to the time required for signal processing, particularly in the case of low-pass filtering. This delay can be problematic in real-time applications.

Environmental Sensitivity: The performance of lock-in amplifiers can be influenced by environmental factors such as temperature variations, electromagnetic interference, and mechanical vibrations, which can affect the stability and accuracy of the measurements.

Bandwidth Limitations: The low-pass filter in lock-in amplifiers determines the bandwidth of the system. Narrow bandwidth filters reduce noise but also limit the response time, making it unsuitable for rapidly changing signals.

2.2.5 APPLICATIONS AND ADVANTAGES OF LOCK-IN TECHNOLOGY

Lock-in technology finds a wide range of applications across various fields due to its unparalleled ability to detect weak signals in the presence of noise. Some key applications and advantages include:

1. **Signal Recovery in Low SNR Environments**:
    - Lock-in amplifiers excel in recovering weak signals buried in noise, making them invaluable tools in low signal-to-noise ratio environments. This capability is particularly useful in scientific experiments, such as spectroscopy, where precise measurements are required under challenging conditions.

2. **Frequency-Selective Measurement**:
    - Lock-in amplifiers enable frequency-selective measurements by isolating signals at specific frequencies while rejecting unwanted noise and interference. This makes them ideal for analyzing modulated signals, conducting frequency response measurements, and characterizing resonant systems.

3. **Non-Destructive Testing and Material Analysis**:
    - In non-destructive testing (NDT) applications, lock-in technology facilitates the detection and characterization of defects or anomalies in materials by sensitively

measuring subtle changes in signal properties. This is essential in industries such as materials science, quality control, and structural health monitoring.

4. **Biomedical Sensing and Imaging:**
    - Lock-in amplifiers play a crucial role in biomedical sensing and imaging applications, where they enable precise detection and measurement of physiological signals, such as bioelectric potentials and optical signals. This enables advancements in medical diagnostics, neuroscience research, and bioimaging techniques

5. **Environmental Monitoring and Remote Sensing:**
    - Lock-in technology is employed in environmental monitoring and remote sensing applications to detect and analyze signals of interest amidst background noise. This includes monitoring atmospheric pollutants, analyzing seismic data, and studying environmental phenomena such as climate change and natural disasters.

In summary, lock-in technology offers unparalleled advantages in signal processing, enabling sensitive detection and measurement of weak signals in noisy environments across diverse scientific and engineering applications. Its versatility and effectiveness make it an indispensable tool for researchers, engineers, and practitioners seeking precise and reliable measurements in challenging conditions.

2.3 LIGHT MEASUREMENT METHODS

Light measurement methods play a crucial role in various fields, including optics, engineering, and environmental science. In this section, we explore different methods of measuring light, considering their relevance to the project and their implications for accurate luminosity measurements.

2.3.1 PHOTOMETRIC VS RADIOMETRIC METHODS

Photometric and radiometric methods represent two fundamental approaches to light measurement, each with its distinct characteristics and applications.

Photometric measurements are made with instruments called photometers. The devices function by collecting light through some kind of input optics, passing it through a spectral modifying filter and then measuring the light with a photosensitive detector. The filter is carefully trimmed to modify the detector response so that it matches the CIE photopic (or scotopic) function. The detector converts the incoming light energy into an electrical signal, which is then amplified and displayed. Because the filter/detector combination approximates the eye response, the measured electrical signal is a true measure of the light as perceived by a human observer. (Inc, n.d.).

Radiometric methods, on the other hand, measure light in terms of its physical properties, such as radiant flux, radiant intensity, and irradiance. These methods consider the entire electromagnetic spectrum and provide quantitative measurements of light energy across different wavelengths. Units such as watts (W), watts per square meter (W/m²), and watts per steradian (W/sr) are commonly used in radiometry. Radiometric measurements are essential for applications where precise characterization of light sources or interactions with matter is required, such as spectroscopy, remote sensing, and photovoltaic efficiency testing. While radiometric methods offer comprehensive insights into the physical properties of light, they may not directly correspond to human visual perception and may require additional calibration for applications related to lighting design and human-centric lighting. (*Technical Note*, n.d.).

2.3.2 COMPARISON OF METHODS

The choice between photometric and radiometric methods depends on the specific requirements and objectives of the light measurement task.

Considerations for Photometric Methods:

- **Human-Centric Applications**: Photometric methods are well-suited for applications where light is perceived by humans, such as architectural lighting design, visual comfort assessments, and interior lighting optimization.
- **Compliance with Standards**: Photometric measurements are often used to assess compliance with lighting standards and regulations, ensuring adequate illumination levels and visual quality in indoor and outdoor environments.
- **Ease of Interpretation**: Photometric quantities, such as illuminance and luminous flux, are directly related to human perception and are easily interpretable in practical lighting applications.

Considerations for Radiometric Methods:

- **Comprehensive Analysis:** Radiometric methods provide detailed information about the spectral distribution and energy content of light, enabling comprehensive analysis of light sources, materials, and environmental interactions.
- **Scientific and Technical Applications**: Radiometric measurements are essential for scientific research, technical analysis, and engineering applications where accurate quantification of light energy is required, such as spectroscopy, remote sensing, and solar energy assessment.
- **Calibration and Instrumentation**: Radiometric measurements may require sophisticated instrumentation and calibration procedures to ensure accuracy and traceability, especially in laboratory and research settings.

In conclusion, the selection of an appropriate light measurement method is crucial for achieving accurate and reliable luminosity measurements in the project context. After careful consideration of photometric and radiometric methods, the project has opted for a photometric approach utilizing the SFH5711 photodiode.

The decision to use the SFH5711 photodiode aligns with the project's objectives and requirements for measuring artificial light in indoor environments. The SFH5711 photodiode offers several advantages that make it well-suited for the project:

1. **Sensitivity to visible light:** The SFH5711 photodiode is specifically designed to detect visible light, making it ideal for applications where human-centric lighting and visual comfort are essential considerations.

2. **High responsivity:** The SFH5711 photodiode exhibits high responsivity in the visible spectrum, allowing for precise detection and quantification of artificial light intensity.

3. **Compact size and low cost:** The SFH5711 photodiode is compact in size and cost-effective, making it suitable for integration into the project's light detection system without significant overhead.

By leveraging the photometric capabilities of the SFH5711 photodiode, the project aims to accurately measure artificial light levels in indoor environments, ensuring compliance with lighting standards and enhancing visual comfort for occupants. The photometric approach offers a practical and efficient solution for addressing the project's objectives, providing valuable insights into lighting conditions while minimizing complexity and cost.

2.4 PHOTODIODES

A photodiode is a semiconductor diode sensitive to photon radiation, such as visible light, infrared or ultraviolet radiation, X-rays and gamma rays. It produces an electrical current when it absorbs photons. This can be used for detection and measurement applications, or for the generation of electrical power in solar cells. Photodiodes are used in a wide range of applications throughout the electromagnetic spectrum from visible light photocells to gamma ray spectrometers. (‘Photodiode’, 2024).

Figure 11.Photodiode symbol. (Fichier, n.d.)

2.4.1 PRINCIPE OF OPERATION

A photodiode is a PIN structure or p–n junction. When a photon of sufficient energy strikes the diode, it creates an electron–hole pair. This mechanism is also known as the inner photoelectric effect. If the absorption occurs in the junction's depletion region, or one diffusion length away from it, these carriers are swept from the junction by the built-in electric field of the depletion region. Thus holes move toward the anode, and electrons toward the cathode, and a photocurrent is produced. The total current through the photodiode is the sum of the dark current (current that is passed in the absence of light) and the photocurrent, so the dark current must be minimized to maximize the sensitivity of the device. (‘Photodiode’, 2024).

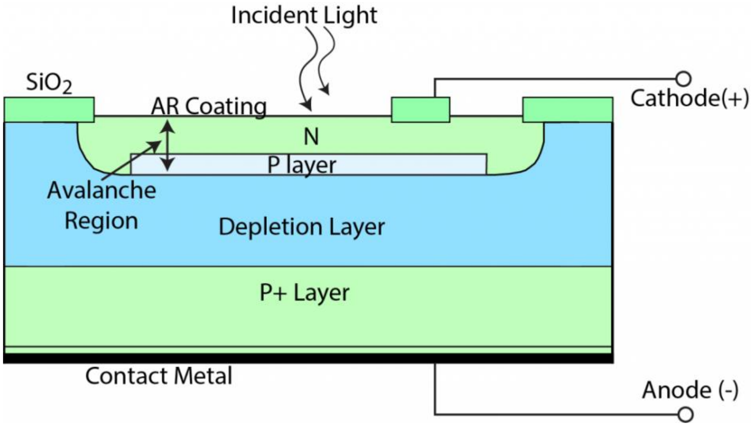

Figure 12. P-N Photodiode Cross-section. (PHOTODIODE BASICS – Wavelength Electronics, n.d.).

In **photovoltaic mode** (zero bias), photocurrent flows into the anode through a short circuit to the cathode. If the circuit is opened or has a load impedance, restricting the photocurrent out of the device, a voltage builds up in the direction that forward biases the diode, that is, anode positive with respect to cathode. If the circuit is shorted or the impedance is low, a forward current will consume all or some of the photocurrent. This mode exploits the photovoltaic effect, which is the basis for solar cells – a traditional solar cell is just a large area photodiode. For optimum power output, the photovoltaic cell will be operated at a voltage that causes only a small forward current compared to the photocurrent.

In **photoconductive mode** the diode is reverse biased, that is, with the cathode driven positive with respect to the anode. This reduces the response time because the additional reverse bias increases the width of the depletion layer, which decreases the junction's capacitance and increases the region with an electric field that will cause electrons to be quickly collected.

Although this mode is faster, the photoconductive mode can exhibit more electronic noise due to dark current or avalanche effects. The leakage current of a good PIN diode is so low (<1 nA) that the Johnson–Nyquist noise of the load resistance in a typical circuit often dominates.

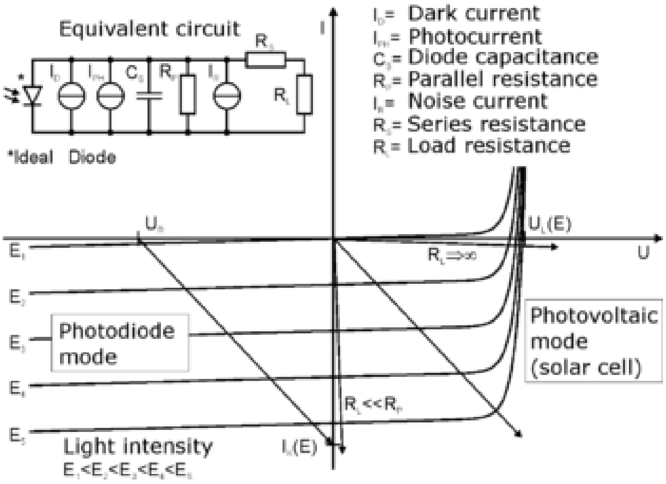

Figure 13. I-V characteristic of a photodiode. (‘Photodiode’, 2024).

Some photodiodes operate in avalanche mode, where a high reverse bias causes a multiplication effect, amplifying the photocurrent. This mode is useful for detecting low light levels but increases noise and requires careful handling.

2.4.2 TYPES AND CHARACTERISTICS

Photodiodes come in various types, each with specific characteristics tailored for different applications. ('Characteristics and use of Photodiodes', 2024).

- **PN Photodiodes**: The most basic type, consisting of a simple p-n junction. They are widely used for general light detection applications due to their simplicity and low cost.
- **PIN Photodiodes**: These photodiodes have an intrinsic layer between the p and n layers, improving performance by reducing capacitance and increasing the response speed. They are ideal for high-speed and high-frequency applications.
- **Avalanche Photodiodes (APDs):** These devices operate with a high reverse bias to achieve internal gain through the avalanche effect. APDs are highly sensitive and can detect very low light levels, making them suitable for applications such as optical communication and LIDAR.
- **Schottky Photodiodes**: These photodiodes use a metal-semiconductor junction instead of a p-n junction, offering fast response times and low capacitance. They are used in high-speed and high-frequency applications.
- **Solar Cells**: Essentially large-area photodiodes designed to convert sunlight into electrical power. They are optimized for energy conversion efficiency rather than speed or sensitivity.

2.4.3 SELECTION CRITERIA

Selecting the appropriate photodiode for a specific application involves considering several factors:

- **Spectral Response**: The photodiode should have a spectral response that matches the wavelength of the light being measured. For example, silicon photodiodes are suitable for visible and near-infrared light, while InGaAs photodiodes are better for mid-infrared light.
- **Responsivity**: This parameter indicates the efficiency with which the photodiode converts light into electrical current. Higher responsivity is desirable for detecting low light levels.
- **Speed and Bandwidth**: The response time and bandwidth of the photodiode are crucial for applications requiring fast signal processing, such as optical communication and high-speed sensing.
- **Noise Performance**: Low noise characteristics are important for achieving high signal-to-noise ratios, especially in low-light conditions.

- **Size and Packaging**: The physical size and packaging of the photodiode should be compatible with the application, whether it is a compact sensor module or a large-area detector.

- **Operating Conditions**: The photodiode should be capable of operating under the specific environmental conditions of the application, including temperature range, humidity, and exposure to light levels.

- **Cost**: Finally, the cost of the photodiode should align with the budget constraints of the project without compromising critical performance requirements.

In the context of this project, the SFH5711 photodiode was selected due to its high responsivity in the visible spectrum, low noise characteristics, and suitability for detecting artificial light under varying environmental conditions. Its compact size and cost-effectiveness further support its integration into the light measurement system, ensuring accurate and reliable performance.

3. CIRCUIT DESIGN AND DEVELOPMENT

This section outlines the design and development of the circuit used in the project. It includes a detailed description of the circuit schematic, along with the roles and functions of each component used in the design.

3.1 CIRCUIT DESCRIPTION

The circuit designed for this project is intended to accurately measure artificial light levels using a photodiode and a lock-in amplifier. The goal is to quantify the amount of artificial light in the presence of natural light and other noise sources. This section provides an overview of the circuit design, the schematic, and the components used.

3.1.1 CIRCUIT SCHEMATIC

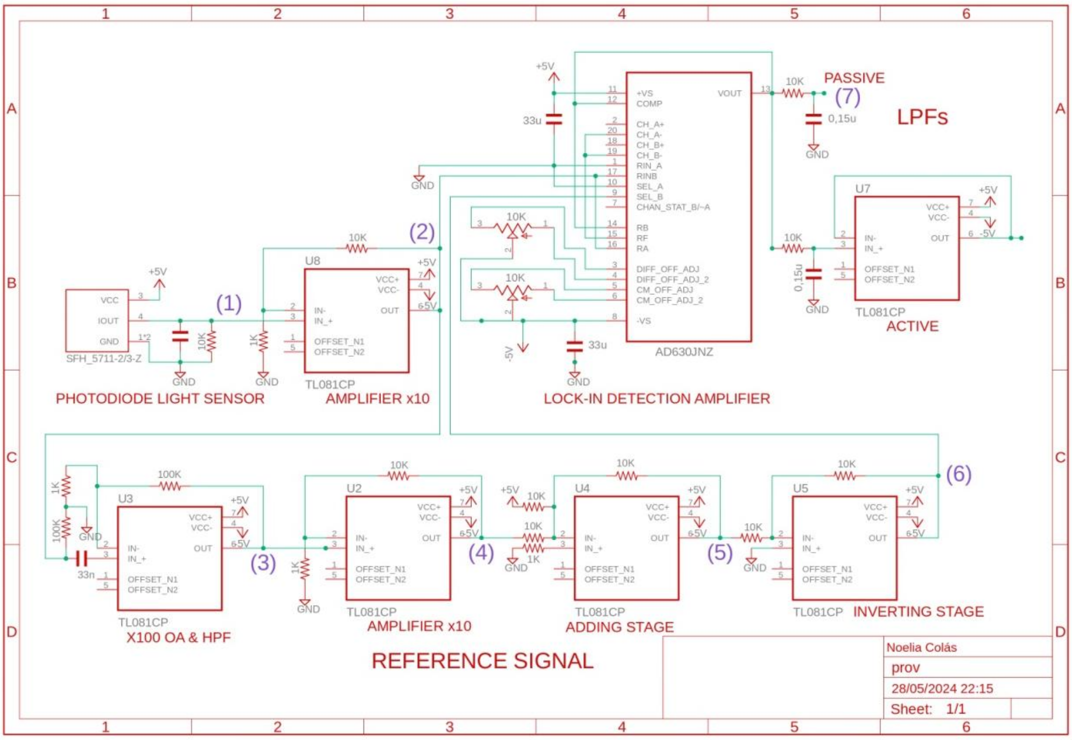

Figure A 1.Circuit Schematic Diagram of the Light Measurement System (see Annex A for full diagram)

3.1.2 DESCRIPTION OF COMPONENTS AND THEIR FUNCTION

The circuit comprises five main stages, each serving a specific function to ensure accurate light measurement and signal processing.

1. **Photodiode Stage:**

- Components: Photodiode, resistor, and capacitor.
- Function: The photodiode converts incident light into an electrical current. The resistor and capacitor at the output are connected to ground to form a simple low-pass filter, which helps to smooth out any high-frequency noise and stabilize the signal.

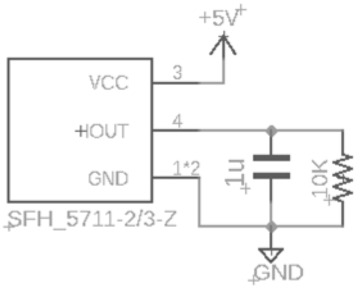

Figure 14.Photodiode stage.

2. **Initial Amplification Stage:**
   - Components: x10 Amplifier.
   - Function: This stage amplifies the weak signal from the photodiode by a factor of 10, making it strong enough for further processing. This initial amplification is crucial to ensure that the signal is above the noise floor of subsequent stages.

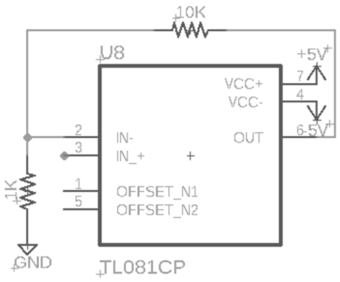

Figure 15. Amplifier stage x10.

3. **Reference Signal Generation Stages:**
   - Stage 1: High-Pass Filter and Amplifier
     - Components: x10 Amplifier with high-pass filter at the input.
     - Function: The high-pass filter removes low-frequency noise and drift, allowing only the desired signal frequencies to pass through. The x10 amplifier then boosts the filtered signal.

   - Stage 2: Cascaded Amplifier
     - Components: Another x10 Amplifier in cascade.
     - Function: Further amplifies the signal by another factor of 10, ensuring that the reference signal is sufficiently strong and clean for accurate synchronization.

   - Stage 3: Summing Stage
     - Components: Summing circuit.

        - Function: Adds a 5-volt DC offset to the signal. This offset is necessary to match the signal level requirements of the subsequent processing stages and ensures that the signal stays within the operational range of the following components.

    - Stage 4: Inverting Stage
        - Components: Inverting amplifier.
        - Function: Inverts the signal phase, this allows to achieve a total positive signal, which can be used as reference.

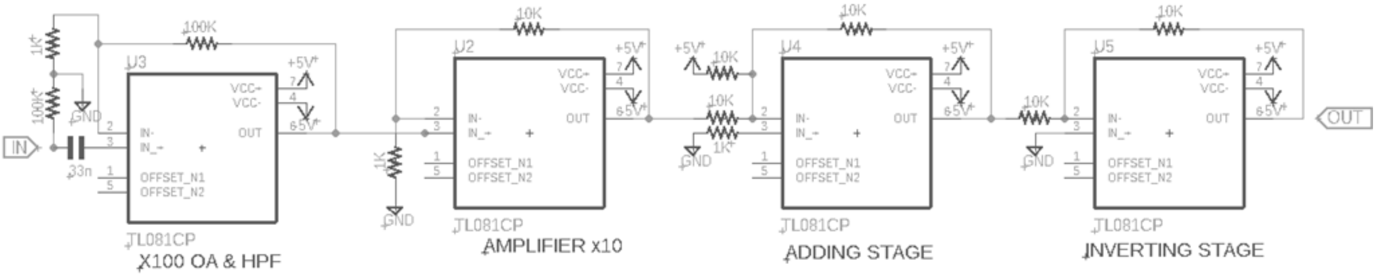

Figure 16. Reference signal stage.

4. **Lock-In Amplifier Stage:**
    - Components: Lock-in amplifier configured with a gain of 1.
    - Function: The lock-in amplifier is a critical component designed to extract the desired signal from a noisy background by using synchronous detection. It processes the amplified signal from the initial stages along with the reference input to isolate the component of the signal at the reference frequency, significantly improving the signal-to-noise ratio.

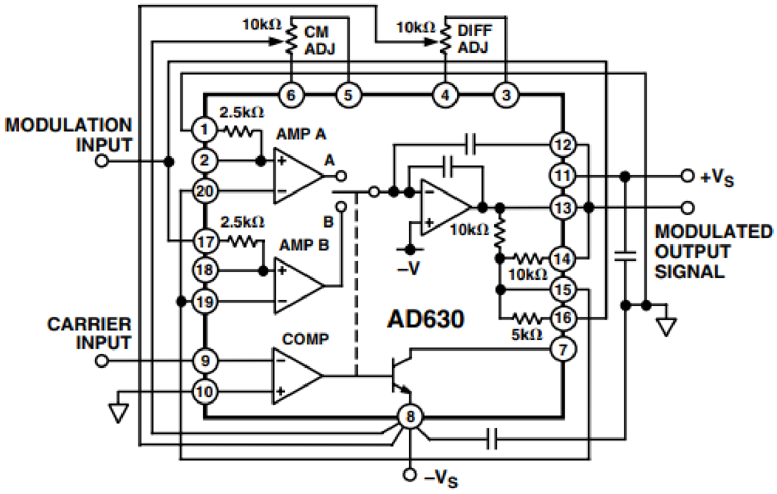

Figure 17. AD630 Configured as a Gain-of-One Balanced Modulator

5. **Final Filtering Stage**:
    - Components: Two parallel low-pass filters (one active, one passive).
    - Function: The low-pass filters remove any remaining high-frequency noise from the output of the lock-in amplifier, ensuring a clean and stable signal. The combination of active and passive filters provides robust noise suppression and smooth signal output, ready for further analysis or display.

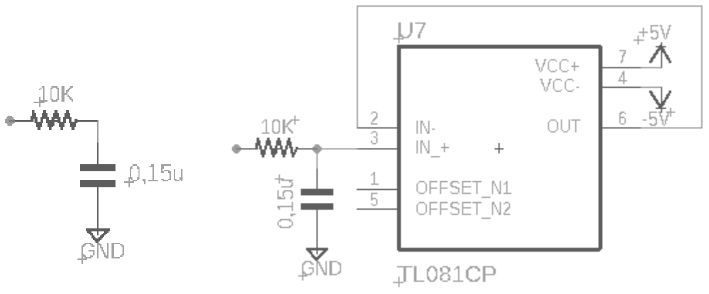

Figure 18. Low pass filters. (Active right, passive left)

3.2 DESIGN PROCESS

The design process for the light measurement circuit involved careful planning and consideration of various factors to ensure optimal performance and reliability. This section outlines the key design considerations and the justification for specific design decisions.

3.2.1 DESIGN CONSIDERATIONS

Constructing a dependable and precise light measurement circuit demands meticulous attention to various factors impacting system performance and dependability. This segment delineates the pivotal design considerations pivotal in the circuit's development. These encompass sensitivity, signal-to-noise ratio, environmental noise, component selection, power consumption, temperature stability, and integration convenience. By methodically addressing these factors, the design endeavours to attain optimal functionality and reliability across real-world scenarios.

1. **Sensitivity and Accuracy:**
    - Consideration: The circuit needs to accurately measure low light levels and provide a high degree of sensitivity to detect subtle changes in light intensity.
    - Implementation: The use of a high-responsivity photodiode (SFH5711) and multiple amplification stages ensures that even small signals can be detected and accurately measured.

2. **Signal-to-Noise Ratio (SNR):**
    - Consideration: Maximizing the SNR is crucial for distinguishing the desired light signal from background noise.

- Implementation: The lock-in amplifier was chosen for its ability to enhance the SNR by synchronously detecting the signal at a specific frequency, effectively filtering out noise.

3. **Environmental Noise and Interference:**
    - Consideration: The circuit must operate reliably in environments with significant electromagnetic interference (EMI) and other noise sources.
    - Implementation: Proper shielding, grounding techniques, and the use of low-pass and high-pass filters were incorporated to mitigate the effects of environmental noise and interference.

4. **Component Selection:**
    - Consideration: Choosing components with appropriate characteristics (e.g., low noise, high precision) is essential for the overall performance of the circuit.
    - Implementation: Components such as low-noise operational amplifiers and precision resistors were selected to minimize additional noise and ensure stable operation.

5. **Power Consumption:**
    - Consideration: The circuit should be energy-efficient, especially if it is intended for portable or battery-powered applications.
    - Implementation: Power-efficient components and design strategies were employed to reduce overall power consumption without compromising performance.

6. **Temperature Stability:**
    - Consideration: Temperature variations can affect the performance of the photodiode and other components.
    - Implementation: Temperature control mechanisms and components with minimal temperature coefficients were chosen to maintain consistent performance across varying temperatures.

7. **Ease of Integration:**
    - Consideration: The circuit should be easily integrated into existing systems and compatible with other components.
    - Implementation: The PCB layout was designed for compactness and ease of connection with other modules, and standard interfaces were used to facilitate integration.

3.2.2 JUSTIFICATION OF DESIGN DECISIONS

Each design decision in the development of the light measurement circuit was made to address specific performance requirements and challenges. This section provides a detailed justification for the major design choices, including the selection of the photodiode, the use of multiple amplification stages, the implementation of a lock-in amplifier, and the integration of filtering strategies. By explaining the rationale behind these decisions, this section highlights how the design meets the project objectives and ensures accurate and reliable light measurements.

1. Use of SFH5711 Photodiode:

- The SFH5711 was selected for its high responsivity in the visible spectrum and low noise characteristics, making it suitable for accurately detecting artificial light in the presence of ambient light.

2. **Multiple Amplification Stages:**
    - Multiple amplification stages (x10 amplifiers) were used to ensure the signal is strong enough for processing. This approach also allows for incremental signal boosting, reducing the risk of introducing excessive noise at any single stage.

3. **Lock-In Amplifier:**
    - The lock-in amplifier was chosen for its superior ability to extract the desired signal from a noisy environment by using synchronous detection. This technique significantly improves the signal-to-noise ratio, which is critical for accurate light measurement.

4. **Filtering Strategies:**
    - High-pass filters were used to eliminate low-frequency noise, while low-pass filters (both active and passive) were employed to remove high-frequency noise. This combination ensures that the signal remains clean and stable throughout the processing stages.

5. **Summing and Inverting Stages:**
    - The summing stage, which adds a 5-volt offset, ensures that the signal level matches the requirements of subsequent stages (making a unipolar signal). The inverting stage is used to make sure we have a positive unipolar signal, since in this way we ensure that we will obtain a positive signal at the output of the lock-in amplifier.

6. **Shielding and Grounding:**
    - Proper electromagnetic shielding and grounding techniques were implemented to reduce EMI and ensure the integrity of the signal, which is essential for accurate measurements in real-world environments.

7. **Component Selection:**
    - Low-noise operational amplifiers and precision resistors were chosen to minimize the introduction of additional noise and to maintain a stable and accurate signal throughout the circuit.

By carefully considering these design factors and making informed decisions, the final circuit design achieves the desired performance characteristics, ensuring reliable and accurate light measurements in various environmental conditions.

4. PCB DEVELOPMENT

The development of the Printed Circuit Board (PCB) for the light measurement system is a critical step when we want to transform the circuit design into a functional prototype. This section describes the design and manufacturing process, the tools and software used and some aspects about PCB design.

4.1 DESIGN AND MANUFACTURING PROCESS

Designing and manufacturing a PCB involves several stages, from schematic capture to final assembly. This section outlines the key steps in the process and the considerations taken to ensure a reliable and high-performance PCB.

4.1.1 TOOLS AND SOFTWARE USED

The design of the PCB was carried out using EAGLE (Easily Applicable Graphical Layout Editor), a powerful PCB design software. EAGLE was chosen for its robust features and ease of use, which are essential for creating complex circuit designs (*EAGLE / Autodesk Fusion Software | Get Prices & Buy Official | Autodesk*, n.d.) .Key features and tools utilized within EAGLE include:

- **Schematic Capture**: Creating detailed circuit schematics that represent the electrical connections and components.
- **Layout Editor**: Designing the physical layout of the PCB, including the placement of components and routing of traces.
- **DRC (Design Rule Check):** Ensuring that the design complies with manufacturing constraints and best practices.
- **Library Management**: Utilizing extensive component libraries to accurately represent each part used in the circuit.
- **Gerber File Generation**: Producing the necessary files for PCB fabrication, including layer information, drill files, and silkscreen details.

Additional tools used during the development process include:

- **SPICE Simulations**: For verifying circuit functionality and performance before physical prototyping.
- **3D Modelling Software**: To visualize the PCB and ensure proper fit within the intended enclosure.

4.1.2 PCB DESIGN

The PCB design process involved several steps to ensure that the final board meets all electrical and mechanical requirements:

1. **Component Placement:**
   - Considerations: Components were strategically placed to minimize signal paths, reduce noise, and ensure ease of assembly. High-frequency components were kept close to each other to minimize interference.
   - Outcome: Optimal placement of the photodiode, amplifiers, filters, and the lock-in amplifier to achieve the desired signal integrity and performance.

2. **Routing:**
   - Considerations: Signal routing was performed to minimize crosstalk and impedance mismatches. Power and ground planes were carefully designed to ensure stable voltage supply and effective grounding.
   - Outcome: Clean and efficient routing of signal, power, and ground traces, ensuring minimal signal degradation and noise.

3. **Layer Stackup:**
   - Considerations: A double-layer PCB was chosen to separate signal and power layers, improving overall performance and reducing electromagnetic interference (EMI).
   - Outcome: A well-organized layer stackup that supports reliable signal transmission and power distribution.

4. **Design for Manufacturability (DFM):**
   - Considerations: The design was optimized to be easily manufactured, assembled, and tested, considering standard PCB manufacturing processes.
   - Outcome: A manufacturable PCB design that adheres to industry standards and can be efficiently produced and assembled.

5. **Prototyping and Testing:**
   - Considerations: After the initial design, prototypes were fabricated and tested to identify any issues and make necessary adjustments.
   - Outcome: Successful prototyping and iteration leading to a final design ready for production.

By following a systematic design and manufacturing process and utilizing advanced tools like EAGLE, a high-quality PCB was developed to meet the requirements of the light measurement system.

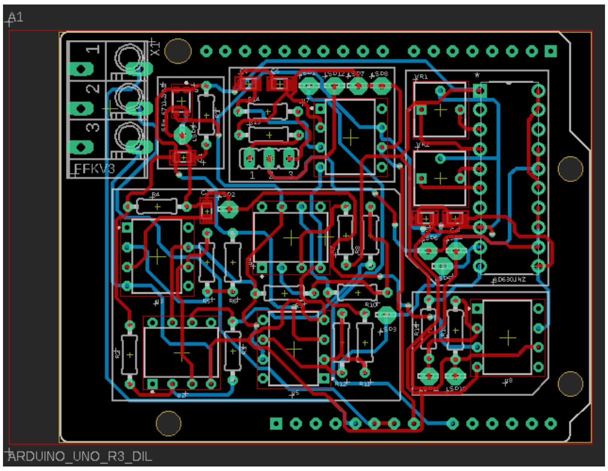

Figure 19. PCB schematic.

4.1.3 PCB LAYOUT AND DESIGN VISUALIZATION

In this section, we present visual representations of the PCB layout and design, highlighting the critical components and stages of the circuit.

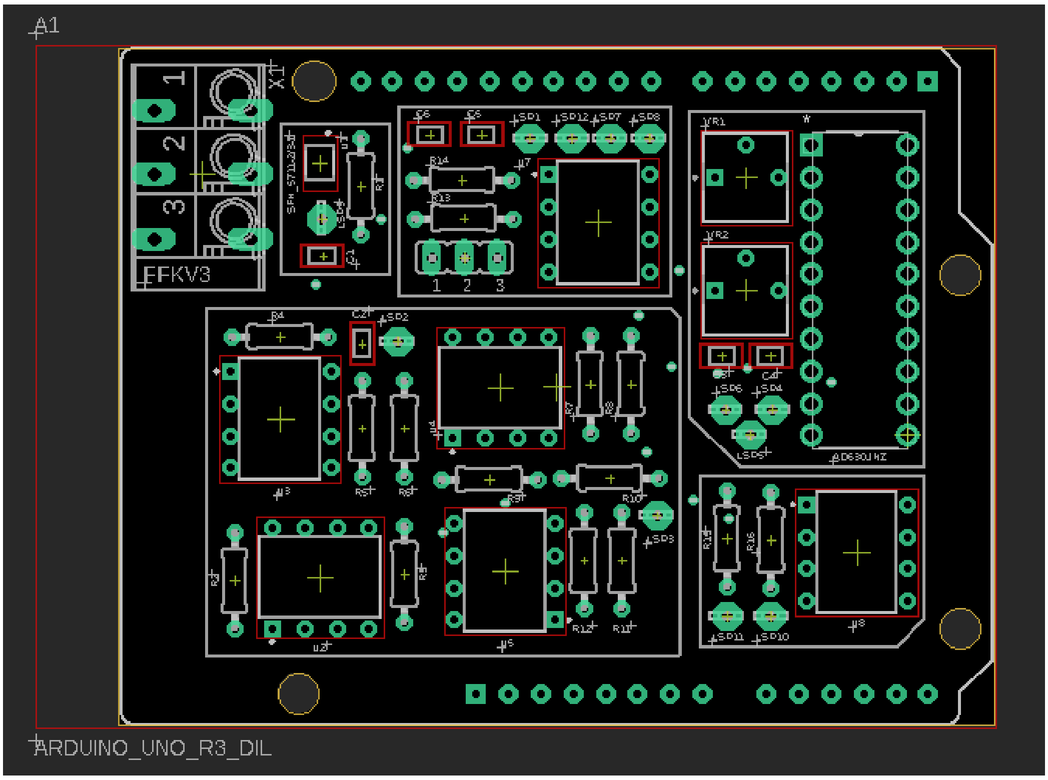

Figure 20. PCB Layout with Circuit Elements.

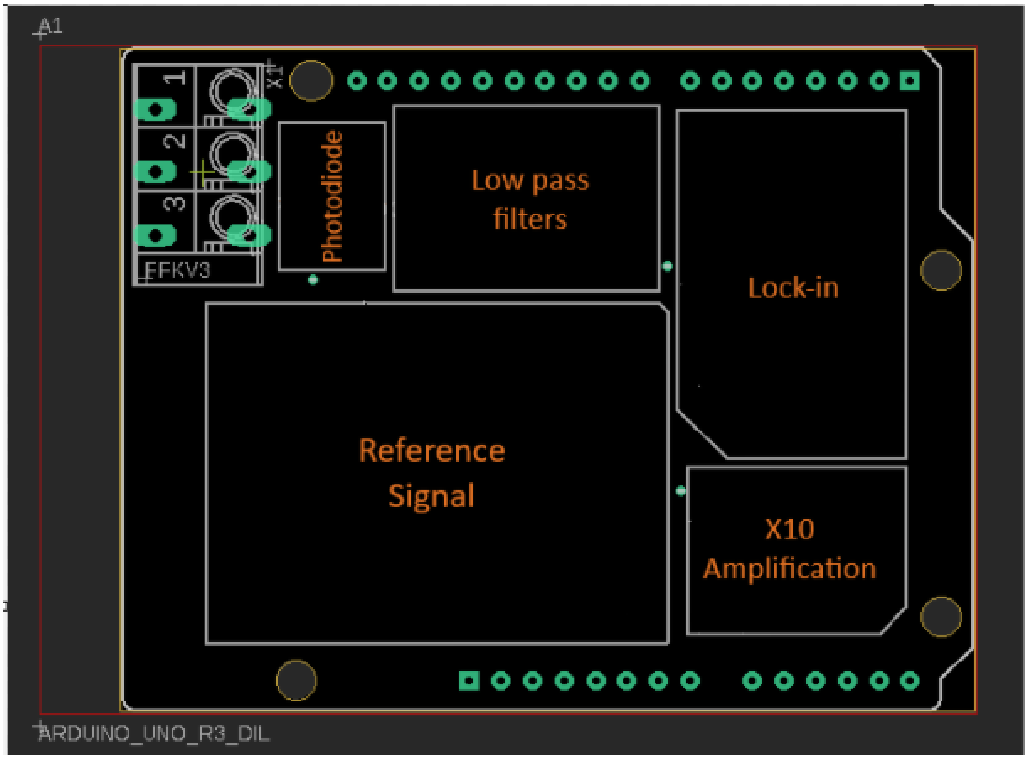

Figure 21. PCB layout with Labelled Stages.

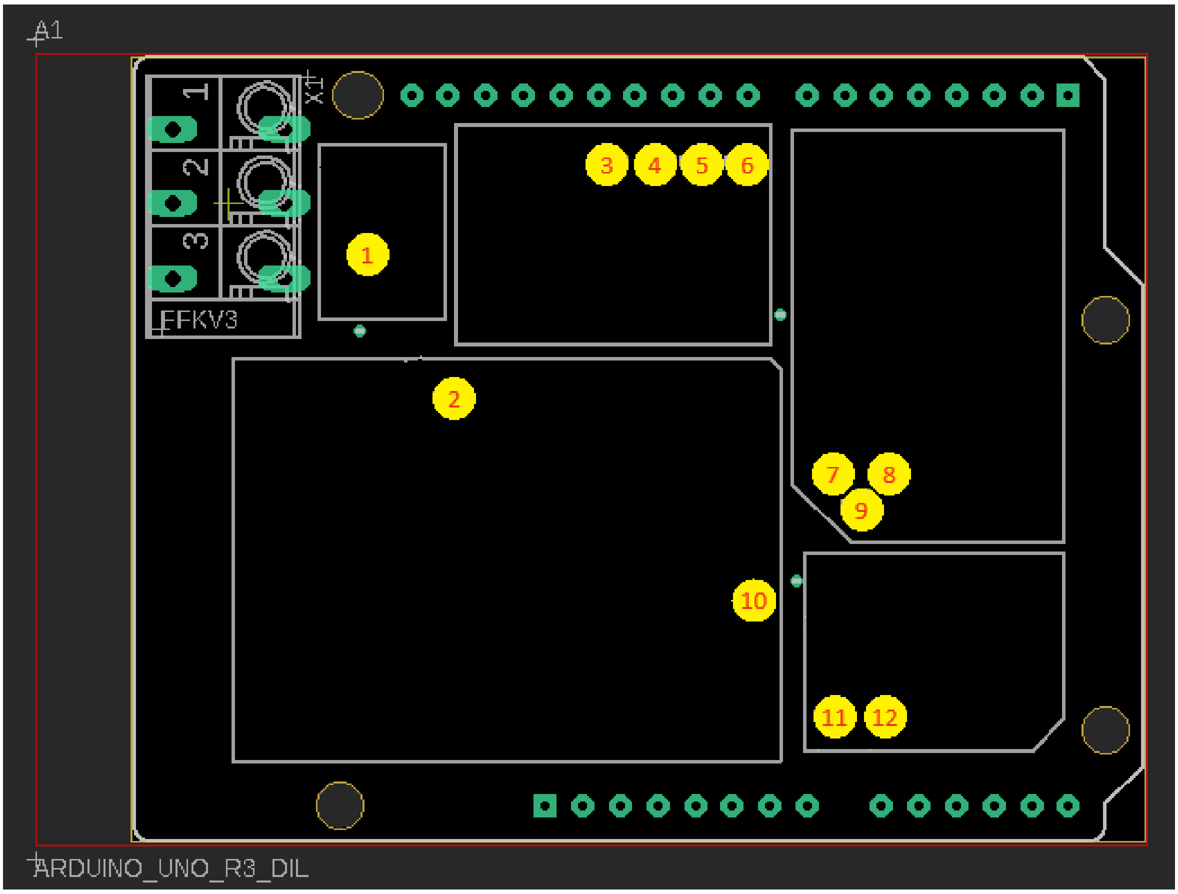

Figure 22. PCB layout with labelled stages and test pads.

Legend: Test Pads

1. **Photodiode output:** This test pad captures the output signal from the photodiode.
2. **Reference input:** This test pad is used for the reference signal input.
3. **Arduino analog input:** This test pad provides the analog input for the Arduino.
4. **Low-pass filter input:** This test pad is for the input to the low-pass filters.
5. **Active low-pass filter output:** This test pad outputs the signal from the active low-pass filter.
6. **Passive low-pass filter output:** This test pad outputs the signal from the passive low-pass filter.
7. **Lock-In amplifier output:** This test pad captures the output signal from the lock-in amplifier.
8. **Signal under study lock-in imput:** This test pad is for the signal under study that is input to the lock-in amplifier.
9. **Reference signal imput to lock-in:** This test pad is for the reference signal input to the lock-in amplifier.
10. **Reference signal output:** This test pad captures the reference signal output.
11. **x10 Amplifier input:** This test pad is for the input signal to the x10 amplifier.
12. **x10 Amplifier output:** This test pad captures the output signal from the x10 amplifier.

4.1.4 PCB ASSEMBLY PROCESS

In this section, we document the PCB assembly process through several images, providing this way a visual and descriptive overview of each step, from the initial layout to the final assembly. This includes photos of the equipment used, the fabrication process, and the final product.

The PCB was fabricated using a ProtoMat S63 milling machine. The materials used include high-quality PCB boards, solder, and various electronic components required for the circuit.

Figure 23. ProtoMat S63 Milling Machine.

Figure 24. Initial PCB layout on ProtoMat S63.

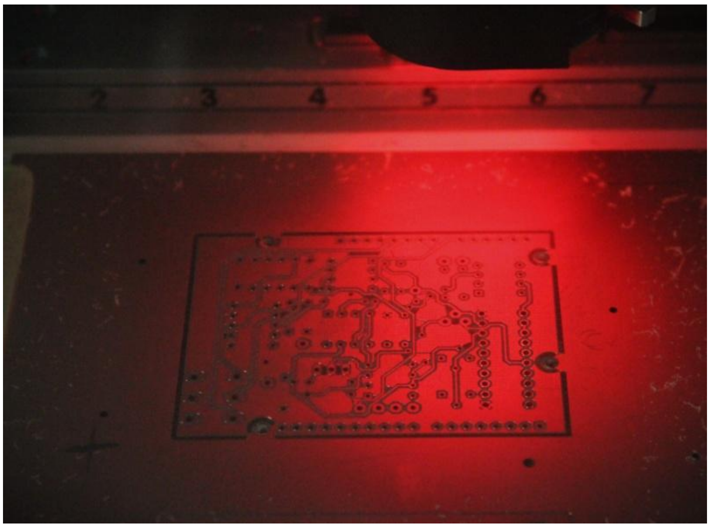

Figure 25. Photo taken during the milling.

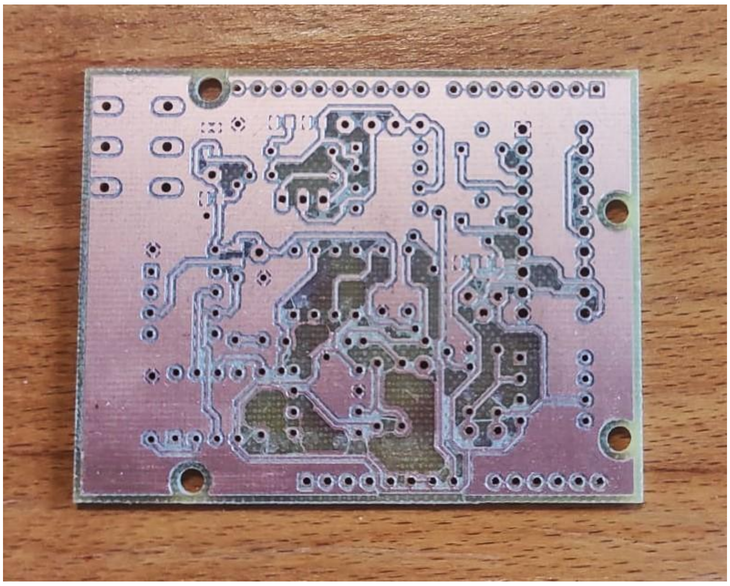

Figure 26.Finished PCB without components.

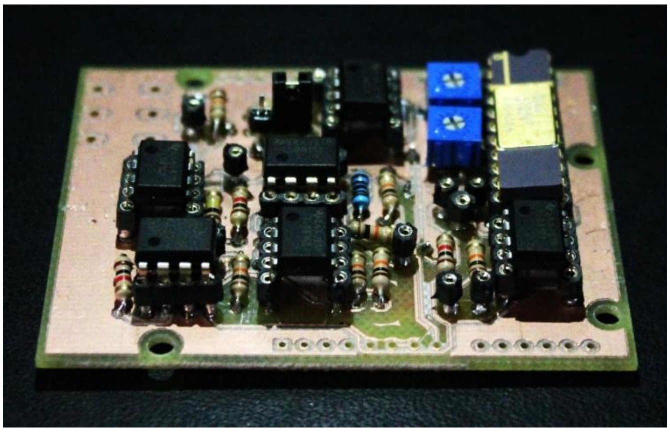

Figure 27. Finished PCB with components.

4.1.5 PROPER ROUTING PRACTICES

Effective PCB routing is crucial for ensuring signal integrity, minimizing noise, and achieving reliable circuit performance. This section outlines best practices for routing high-speed PCBs, drawing on guidelines to optimize the design for both electrical performance and manufacturability. (Shashikanth, 2020)

1. **Minimize Trace Lengths:**
   - Objective: Reduce signal path lengths to minimize delays and signal degradation.
   - Implementation: Critical signal traces, especially high-frequency ones, were kept as short and direct as possible to prevent issues such as reflection and attenuation.

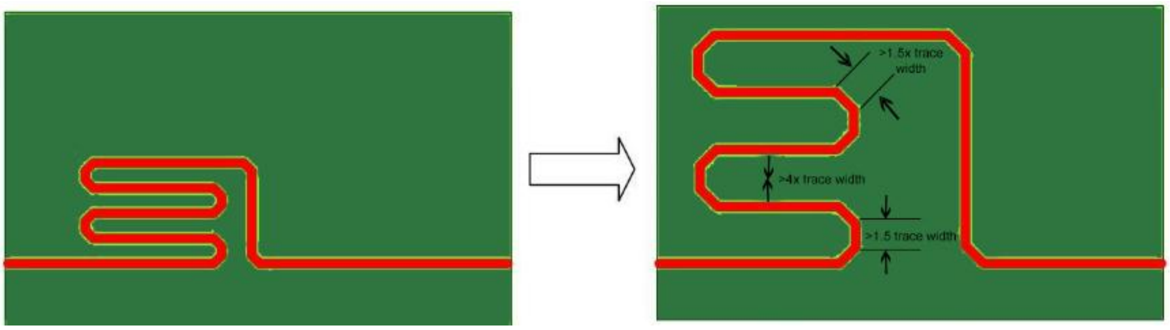

Figure 28.Keep minimum distance and segment length at bends. (Shashikanth, 2020)

2. **Controlled Impedance Routing:**
   - Objective: Maintain consistent impedance to prevent signal distortion and ensure signal integrity.
   - Implementation: Impedance-controlled traces were routed with careful consideration of width, spacing, and the dielectric properties of the PCB material. Differential pairs were used where appropriate, with precise spacing to maintain uniform impedance.

3. **Use of Ground Planes:**
   - Objective: Provide a continuous reference plane for signals and reduce EMI.
   - Implementation: Dedicated ground planes were included in the PCB stackup. Ground planes were kept intact and continuous under high-speed signal traces to provide a return path with minimal inductance.

4. **Avoiding Crosstalk:**
   - Objective: Minimize interference between adjacent signal traces.
   - Implementation: Adequate spacing was maintained between parallel signal traces to reduce crosstalk. Critical signal traces were routed on separate layers, and ground planes were used to shield sensitive signals.

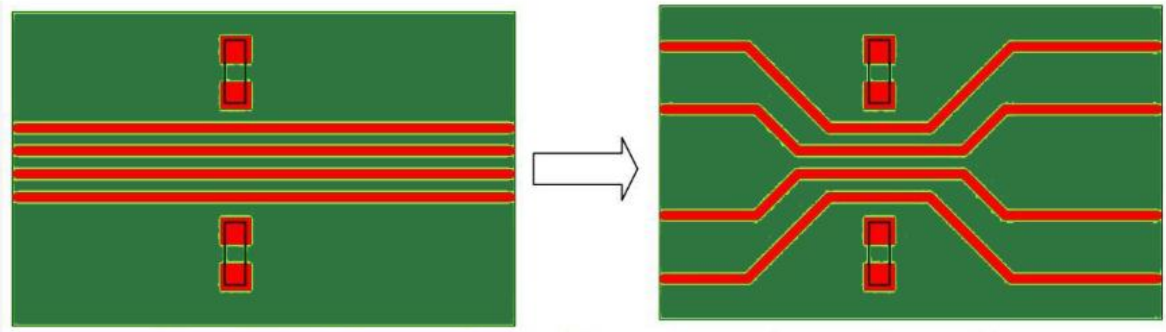

Figure 29. Increasing the space between traces to prevent crosstalk. (Shashikanth, 2020)

5. **Layer Stackup Design:**
    - Objective: Optimize layer arrangement to support signal integrity and power distribution.
    - Implementation: A balanced layer stackup was designed, with signal layers adjacent to ground or power planes. High-speed signal layers were sandwiched between ground planes to minimize EMI and maintain signal quality.

6. **Power and Ground Routing:**
    - Objective: Ensure stable power delivery and effective grounding.
    - Implementation: Power traces were kept wide to reduce voltage drops, and multiple vias were used to connect power and ground planes, providing robust grounding and minimizing loop inductance.

7. **Via Management:**
    - Objective: Minimize signal degradation and maintain integrity.
    - Implementation: The number of vias was minimized on high-speed traces to reduce signal reflections and losses. When necessary, vias were carefully placed and spaced to mitigate their impact on signal integrity.

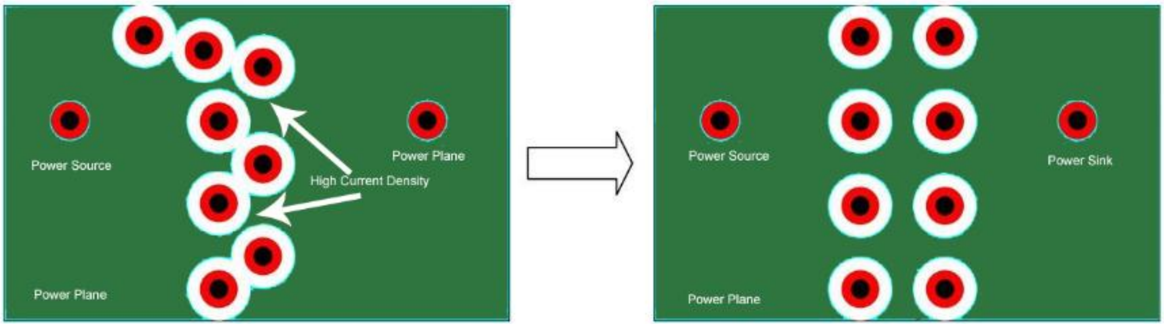

Figure 30. Route vias in a grid pattern to avoid hotspots. (Shashikanth, 2020)

By adhering to these routing practices, the design ensures robust signal integrity, minimizes electromagnetic interference, and achieves reliable operation of the light measurement system. These routing strategies are essential for maintaining the performance and reliability of the circuit, particularly in high-frequency applications.

4.2 ASSEMBLY AND SOLDERING

The assembly and soldering of the PCB are critical steps to ensure the functionality and reliability of the light measurement circuit. Proper techniques and best practices must be followed to avoid damage to components and ensure long-term performance.

4.2.1 ASSEMBLY TECHNIQUES

The assembly of the PCB involves various techniques to place and secure components onto the board. The chosen assembly methods significantly impact the performance, reliability, and manufacturability of the final product. This section provides an overview of the different assembly techniques employed in this project, including Surface Mount Technology (SMT), Through-Hole Technology (THT), and mixed technology approaches. Each technique is selected based on the specific requirements of the components and the overall design of the PCB.

1. **Surface Mount Technology (SMT):**

    - Process: Surface mount components are placed onto the PCB using automated pick-and-place machines. These components are then soldered using a reflow soldering process.
    - Advantages: SMT allows for higher component density, better performance at high frequencies, and reduced parasitic elements compared to through-hole components.
    - Application: Most of the components, including resistors, capacitors, and ICs, are surface-mounted to ensure compact and efficient PCB layout.

2. **Through-Hole Technology (THT):**

    - Process: Through-hole components are inserted into pre-drilled holes on the PCB and then soldered manually or using wave soldering.
    - Advantages: Through-hole components provide stronger mechanical bonds and are suitable for components that require higher power or mechanical stability.
    - Application: Used for components like connectors and large capacitors that need stronger physical connections.

3. **Mixed Technology:**

    - Process: Combines both SMT and THT on the same PCB to leverage the advantages of both techniques.
    - Advantages: Provides flexibility in component placement and optimization of PCB design.
    - Application: Ensures the best use of space and performance characteristics for the light measurement circuit.

4. **Manual Assembly:**

    - Process: Components that cannot be placed by machines or require special handling are assembled manually using precision tools.

- Advantages: Allows for custom and precise placement of critical components.
- Application: Used for components that require careful alignment or special soldering techniques.

4.2.2 PRECAUTIONS AND BEST PRACTICES

Ensuring the proper assembly and soldering of the PCB requires adherence to a set of precautions and best practices. These measures are essential to prevent damage to sensitive components, maintain the integrity of solder joints, and achieve a reliable final product. This section outlines the key precautions to take during assembly and soldering, such as handling components to prevent electrostatic discharge (ESD), maintaining proper soldering temperatures, and ensuring thorough cleaning and inspection. By following these best practices, the likelihood of assembly errors and component failures is minimized, leading to a robust and functional PCB.

1. **Handling Components:**
    - Precaution: Electrostatic discharge (ESD) can damage sensitive components.
    - Best Practice: Use ESD-safe workstations, wrist straps, and anti-static mats. Handle components with care and store them in anti-static packaging.

2. **Soldering Temperature:**
    - Precaution: Excessive heat can damage components and PCB materials.
    - Best Practice: Use temperature-controlled soldering irons and reflow ovens. Follow manufacturer-recommended soldering temperatures and profiles.
3. **Component Placement:**
    - Precaution: Incorrect placement can cause malfunction or circuit failure.
    - Best Practice: Verify component orientation and placement before soldering. Use magnification tools for precise alignment.

4. **Solder Joint Quality:**
    - Precaution: Poor solder joints can lead to intermittent connections and circuit failures.
    - Best Practice: Ensure proper wetting of solder joints with a shiny, smooth appearance. Inspect solder joints using microscopes or magnifying glasses.

5. **Cleaning:**
    - Precaution: Residual flux and contaminants can cause corrosion and electrical leakage.
    - Best Practice: Clean the PCB thoroughly after soldering using appropriate solvents and cleaning tools. Ensure the PCB is dry and free of residues.

6. **Thermal Management:**
    - Precaution: Improper thermal management can lead to overheating and component failure.

  - Best Practice: Implement thermal relief pads for heat-sensitive components. Use heatsinks and thermal vias where necessary.

7. **Inspection and Testing:**
    - Precaution: Undetected assembly errors can result in faulty circuits.
    - Best Practice: Perform thorough inspections using automated optical inspection (AOI) and manual visual inspection. Test the assembled PCB for functionality before deployment.

8. **Rework and Repair:**
    - Precaution: Excessive rework can damage the PCB and components.
    - Best Practice: Use specialized rework stations for desoldering and component replacement. Follow controlled rework procedures to minimize damage.

By following these assembly techniques and adhering to the outlined precautions and best practices, the PCB for the light measurement circuit can be assembled reliably, ensuring optimal performance and durability.

5. ELECTROMAGNETIC COMPATIBILITY (EMC)

Electromagnetic compatibility (EMC) is the ability of electrical equipment and systems to function acceptably in their electromagnetic environment, by limiting the unintentional generation, propagation and reception of electromagnetic energy which may cause unwanted effects such as electromagnetic interference (EMI) or even physical damage to operational equipment. The goal of EMC is the correct operation of different equipment in a common electromagnetic environment. ('Electromagnetic Compatibility', 2024).

This section discusses the importance of Electromagnetic Compatibility in PCB design, focusing on the specific measures taken to ensure that the light measurement circuit operates reliably without causing or being affected by electromagnetic interference (EMI).

5.1 EMC IN PCB DESIGN

From research and development to final certification, electromagnetic compatibility (EMC) principles should be a key focus of electronics product design. In addition to ensuring product safety and wireless coexistence, considering EMC principles in the early stages helps smooth the path to compliance and prevents costs and time associated with redesign. (*EMC Principles for Electronics Product Design*, n.d.)

5.1.1 IMPORTANCE OF EMC

Electromagnetic Compatibility (EMC) is a critical consideration in PCB design, especially for circuits involving sensitive measurements, such as the light detection system in this project. EMC ensures that the electronic device can operate correctly within its electromagnetic environment and does not introduce excessive electromagnetic interference (EMI) to other systems. Achieving good EMC is vital for maintaining the functional integrity, reliability, and compliance with regulatory standards of electronic devices. In this section, we will explore why EMC is essential and how it impacts the performance and reliability of our light detection circuit.

- **Functional Integrity:** Ensures that the photodiode and lock-in amplifier operate accurately without disruption from external electromagnetic sources.

- **Compliance with Standards:** Adheres to regulatory requirements for electromagnetic emissions and susceptibility, which is essential for commercial viability.

- **Reliability:** Enhances the reliability and longevity of the circuit by preventing malfunction or degradation due to EMI.

5.1.2 DESIGN CONSIDERATIONS FOR EMC

Effective EMC design involves a variety of strategies and practices aimed at minimizing electromagnetic interference and ensuring the proper functioning of electronic circuits. This section delves into the key design considerations and techniques employed to enhance EMC in the PCB design of our light detection circuit. We will discuss the implementation of shielding, grounding, filtering, and optimal PCB layout practices, all of which are crucial for reducing EMI and ensuring the circuit's performance is not compromised by external or internal electromagnetic disturbances.

- **Shielding:** Implementing shielding techniques to protect sensitive components from external EMI. For example, using a grounded metal enclosure around the photodiode and lock-in amplifier.

- **Grounding**: Establishing a robust grounding scheme to minimize ground loops and voltage differences, which can introduce noise.

- **Filtering**: Using capacitors and inductors to filter out unwanted high-frequency noise from power and signal lines.

- **PCB Layout**: Optimizing the PCB layout to minimize EMI, such as separating analog and digital ground planes, keeping high-speed traces short, and using differential pair routing where applicable.

5.2 EMI SOURCES AND MIGRATION TECHNIQUES

Understanding the sources of EMI and implementing appropriate mitigation techniques is essential to achieving EMC in the PCB design. This section outlines common EMI sources and the strategies used to minimize their impact.

5.2.1 EMI SOURCES

Electromagnetic Interference (EMI) can originate from a variety of sources, both external and internal to the electronic device. External sources such as power lines, radio transmitters, and industrial equipment can introduce significant interference, while internal sources, including switching power supplies, clock signals, and digital circuits, can generate noise within the system. This section will identify and describe the common sources of EMI that could affect the performance of the light detection circuit, highlighting the challenges posed by each.

External Sources:

- Power Lines: High-voltage power lines can induce noise into the circuit.
- Radio Transmitters: Nearby radio frequency transmitters can introduce radiative EMI.

- Industrial Equipment: Heavy machinery and other industrial equipment can generate significant EMI.

Internal Sources:

- Switching Power Supplies: Switching regulators can introduce noise into the circuit.
- Clock Signals: High-frequency clock signals can radiate EMI.
- Digital Circuits: Fast switching digital circuits can create noise that couples into sensitive analog sections.

5.2.2 MITIGATION TECHNIQUES

Mitigating EMI is essential for achieving robust electromagnetic compatibility in PCB design. Various techniques can be employed to minimize the impact of EMI, ensuring that the circuit functions correctly and reliably in its intended environment. This section will explore a range of mitigation strategies, including shielding, filtering, grounding practices, and PCB layout considerations. By implementing these techniques, we can effectively reduce the susceptibility of the light detection circuit to EMI and enhance its overall performance.

- **Shielding Techniques:**
    - Metal Enclosures: Enclosing the circuit in a metal case to block external radiative EMI.
    - Ground Planes: Using continuous ground planes to provide a low impedance path for EMI.

- **Filtering Strategies:**
    - Power Line Filters: Implementing low-pass filters on power lines to block high-frequency noise.
    - Signal Line Filters: Using ferrite beads and capacitors on signal lines to suppress EMI.

- **Grounding Practices:**
    - Single-Point Grounding: Connecting all grounds at a single point to prevent ground loops.
    - Separated Ground Planes: Keeping analog and digital grounds separate to avoid cross-coupling of noise.

- **PCB Layout Considerations:**
    - Short Traces: Keeping high-speed signal traces as short as possible to minimize radiation.
    - Trace Routing: Avoiding sharp angles in traces and using curved traces to reduce EMI radiation.
    - Component Placement: Placing sensitive components away from noisy sections of the PCB.

  - Decoupling Capacitors: Placing decoupling capacitors close to the power pins of ICs to filter high-frequency noise.

By incorporating these EMC principles and mitigation techniques, the light measurement circuit can be designed to operate effectively and reliably in its intended environment, ensuring that it meets both functional and regulatory requirements.

6. RESULTS ANALYSIS

This section presents and discusses the results obtained from the light detection circuit. The results are analyzed to evaluate the performance and effectiveness of the design, comparing them with other methods and providing a statistical analysis to support the findings.

6.1 PRESENTATION OF RESULTS

Here, we will present the data collected from the light detection circuit, including oscilloscope measurements of signals at various stages of the circuit. This presentation will provide a clear understanding of how the circuit performs under different conditions.

6.1.1 DATA OBTAINED

In this subsection, we present the raw data obtained from testing the light detection circuit. The data includes oscilloscope readings from various stages of the circuit, capturing signal amplitudes, noise levels, and the impact of the lock-in amplifier. Measurements were taken under controlled lighting conditions to ensure consistency and accuracy.

Photodiode Stage: At this stage, the signal directly from the photodiode is measured to assess the initial light detection capability and baseline noise.

Table 1. Signal data in the photodiode stage.

Light		VOLTAGE (mV)
Natural light	1	32
	2	32
	3	32
Natural + artificial light	1	40
	2	32
	3	40
Artificial light	1	28
	2	28
	3	28

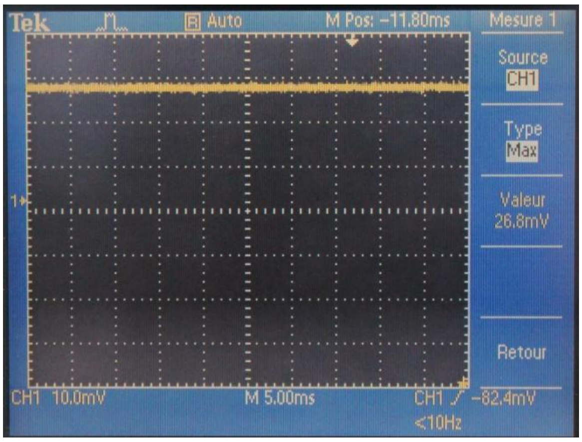

Figure 31. Photodiode stage

The signal from the photodiode shows an initial value of 32 mV at natural and artificial conditions, with noticeable noise spikes indicating the presence of both the desired signal and background noise.

First Amplification Stage (x10): The first amplification stage amplifies the signal from the photodiode by a factor of 10.

Table 2. Signal data in the x10 amplification stage.

Light		VOLTAGE (mV)
Natural light	1	256
	2	260
	3	256
Natural + artificial light	1	296
	2	296
	3	296
Artificial light	1	256
	2	256
	3	256

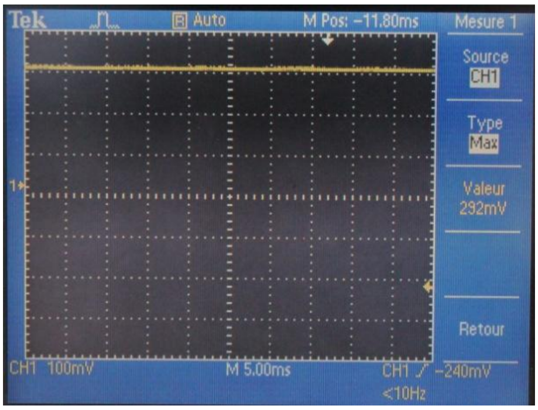

Figure 32. x10 amplifier stage

The amplified signal shows a tenfold increase in amplitude, with a proportional increase in noise, highlighting the need for further processing.

Stage (x100) with HPF: amplifies the signal by a factor of 100 and includes a high-pass filter to eliminate low-frequency noise.

Table 3. Signal data in the x100 amplification + HPF stage.

Light		VOLTAGE AMPLITUDE (mV)
Natural light	1	8
	2	16
	3	8
Natural + artificial light	1	280
	2	280
	3	280
	1	496

Artificial light	2	496
	3	496

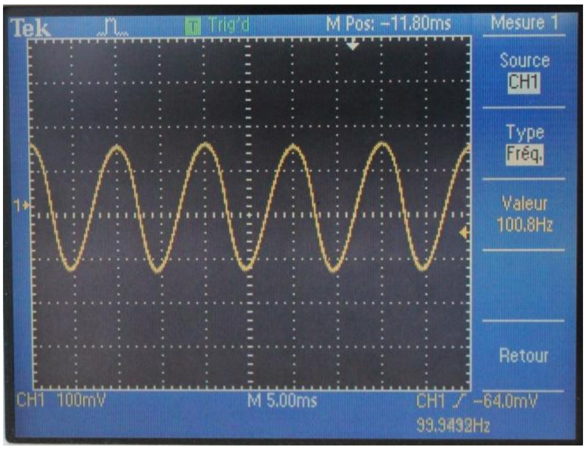

Figure 33. X100 + HPF stage.

As we can see, we obtain a perfectly sinusoidal signal with a frequency of 100Hz after filtering out the DC component with the high-pass filter. The problem is that in order to have a reference signal that the lock-in amplifier can use, this signal must be entirely positive, which we can see is not the case.

Second Amplification Stage (x10): this amplification stage amplifies the signal for the reference by a factor of 10.

Table 4. Signal data in the x10 amplification of the reference stage.

Light		VOLTAGE AMPLITUDE (mV)
Natural light	1	48
	2	56
	3	56
Natural + artificial light	1	792
	2	800
	3	792
Artificial light	1	800
	2	800
	3	792

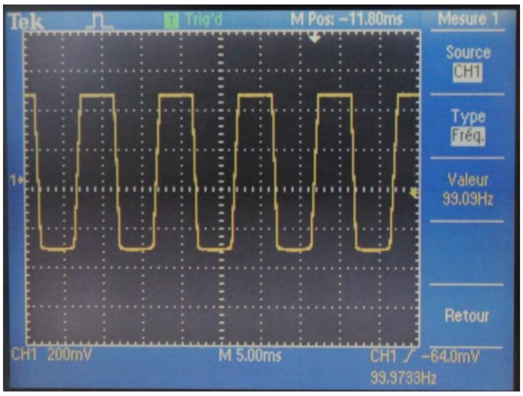

Figure 34. x10 amplification stage.

In this amplification stage, we observe a notable change in the signal characteristics. Initially, the signal was sinusoidal, representing a clean and continuous waveform. However, after amplification, the signal has become somewhat squared. This squaring effect is likely due to the amplifier reaching its maximum output limits, causing clipping at the peaks of the waveform. Anyway, this shouldn't matter to us, as what really matters is that the frequency of the signal remains the same (it continues to match the frequency of the signal under study).

Summing stage: the summing stage adds 5V offset to make sure that the signal will always be positive.

Table 5. Signal data in the summing stage.

Light		VOLTAGE AMPLITUDE (mV)
Natural light	1	8
	2	8
	3	8
Natural + artificial light	1	208
	2	216
	3	216
Artificial light	1	208
	2	216
	3	208

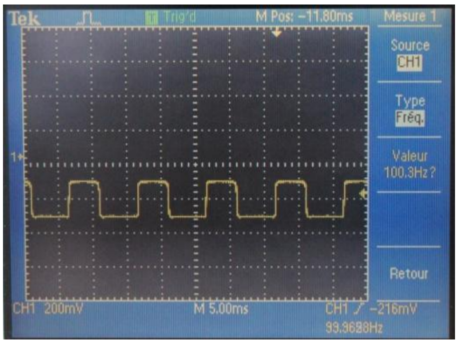

Figure 35. Summing stage.

Now, we can appreciate that our signal is entirely within the negative plane, which is positive since we need a unipolar signal. If we were to leave the reference signal this way, the output signal of the AD630 amplifier would result in another negative signal, which is not usually the best option. Therefore, we will require an inverting stage later on.

Inverting stage: reverses the signal polarity.

Table 6. Signal data in the inverting stage.

Light		VOLTAGE AMPLITUDE (mV)
	1	16

Natural light	2	16
	3	16
Natural + artificial light	1	216
	2	216
	3	216
Artificial light	1	216
	2	216
	3	216

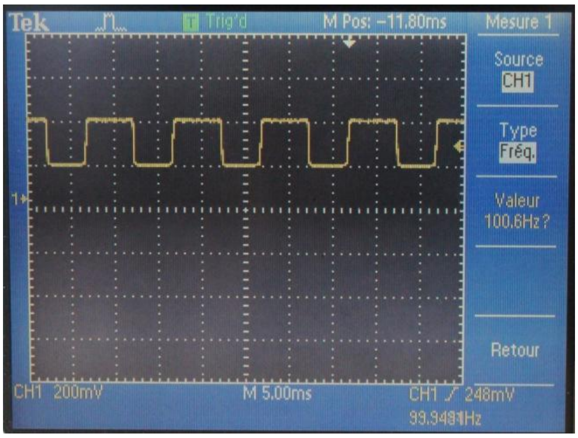

Figure 36. Inverting stage.

By implementing the inverting stage, we can effectively shift the signal from the negative plane to the positive plane. This adjustment ensures that the reference signal is not only unipolar but also positive, aligning with the requirements for optimal operation of the lock-in amplifier. Thus, the inverting stage is essential in maintaining the integrity and usability of the reference signal throughout the system.

Lock-in amplifier and LPF stage: The lock-in amplifier is configured with a gain of 1, designed to demodulate and isolate the artificial light signal from background noise. We add the LPF at the output of the amplifier to filter any undesired noise at the output.

Table 7. Signal data in the lock-in amplifier and LPF stage.

Light		VOLTAGE (mV)
Natural light	1	264
	2	264
	3	257
Natural + artificial light	1	304
	2	304
	3	304
Artificial light	1	272
	2	272
	3	272

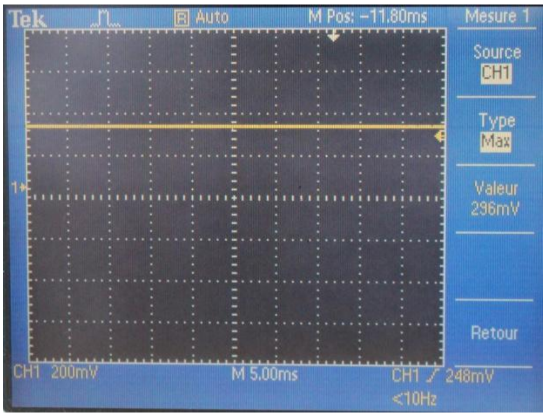

Figure 37. Lock-in amplifier and LPF stage.

The sensor's experimental data collected under three different lighting conditions—natural light only, combined natural and artificial light, and artificial light only—showed distinct voltage outputs at the circuit's output. Specifically, the measurements were 264 mV for natural light, 304 mV for combined natural and artificial light, and 272 mV for artificial light. These variations in voltage demonstrate the sensor's ability to differentiate between the lighting conditions, with the highest voltage occurring in the combined light scenario. This confirms the successful operation of the lock-in amplifier and the system's overall effectiveness in measuring artificial light even when natural light is present.

In conclusion, the lock-in amplifier, through synchronous detection, isolates the signal at the modulation frequency, significantly improving the signal-to-noise ratio. The subsequent low-pass filter stage further cleans the signal by removing high-frequency noise, allowing only the desired frequency components to pass through. This two-stage process ensures that the final output signal is both clean and precise, making it suitable for accurate measurements and analysis.

6.2 DISSCUSION OF RESULTS

In this section, we delve into a comprehensive discussion and analysis of the results obtained from our experiments and measurements. The discussion encompasses a comparison between the boxcar averager and the lock-in amplifier as alternative signal processing methods, followed by a qualitative analysis of the collected data. This discussion serves to deepen our understanding of the experimental outcomes and provides a basis for further exploration and refinement in future research endeavours.

6.2.1 COMPARISON WITH OTHER METHODS: BOXCAR AVERAGER

In the realm of signal processing and measurement, the choice of amplification and noise reduction techniques is pivotal in extracting meaningful information from noisy environments. Among the array of available options, the boxcar averager emerges as a compelling alternative, particularly in scenarios where the primary objective is to mitigate high-frequency noise while preserving the essential characteristics of the signal under study. The boxcar averager operates on the principle of temporal integration, smoothing out fluctuations over a defined time window to enhance the signal-to-noise ratio. (*Lock-in Amplifier or Boxcar Averager*, 2023)

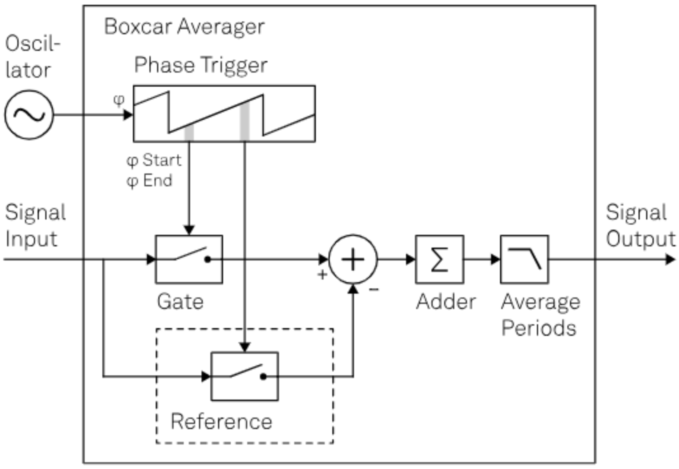

Figure 38. Boxcar Averager schematic. (Principles of Boxcar Averaging | Zurich Instruments, 2022)

Advantages of using a Boxcar average instead of a lock-in detection amplifier:

1. **Simplicity**: The boxcar averager is straightforward to implement, especially in analog circuitry.
2. **Noise Reduction**: It is effective in reducing random high-frequency noise, which is useful for signals with significant noise components.
3. **Cost-Effective**: Generally, boxcar averagers can be more cost-effective than sophisticated digital signal processing or lock-in amplifiers.
4. **Real-Time Processing**: Provides immediate results without the need for complex calculations.

Disadvantages

1. **Resolution Loss**: Averaging can result in a loss of temporal resolution, as fine details within the averaging window may be smoothed out.
2. **Not Frequency-Specific**: Unlike lock-in amplifiers, which can isolate signals at specific frequencies, boxcar averagers do not differentiate between frequencies within the averaging window.
3. **Fixed Averaging Window**: The performance is highly dependent on the choice of the averaging window. A poor choice can lead to suboptimal noise reduction.

Taking in account that this project involves measuring light signals and dealing with noise, the boxcar averager can be a suitable alternative if:

- The main challenge is high-frequency noise that you can average out without losing critical signal information.

- The signals you are dealing with are relatively stable and do not require high temporal resolution within the averaging period.
- The implementation complexity and cost need to be kept low.

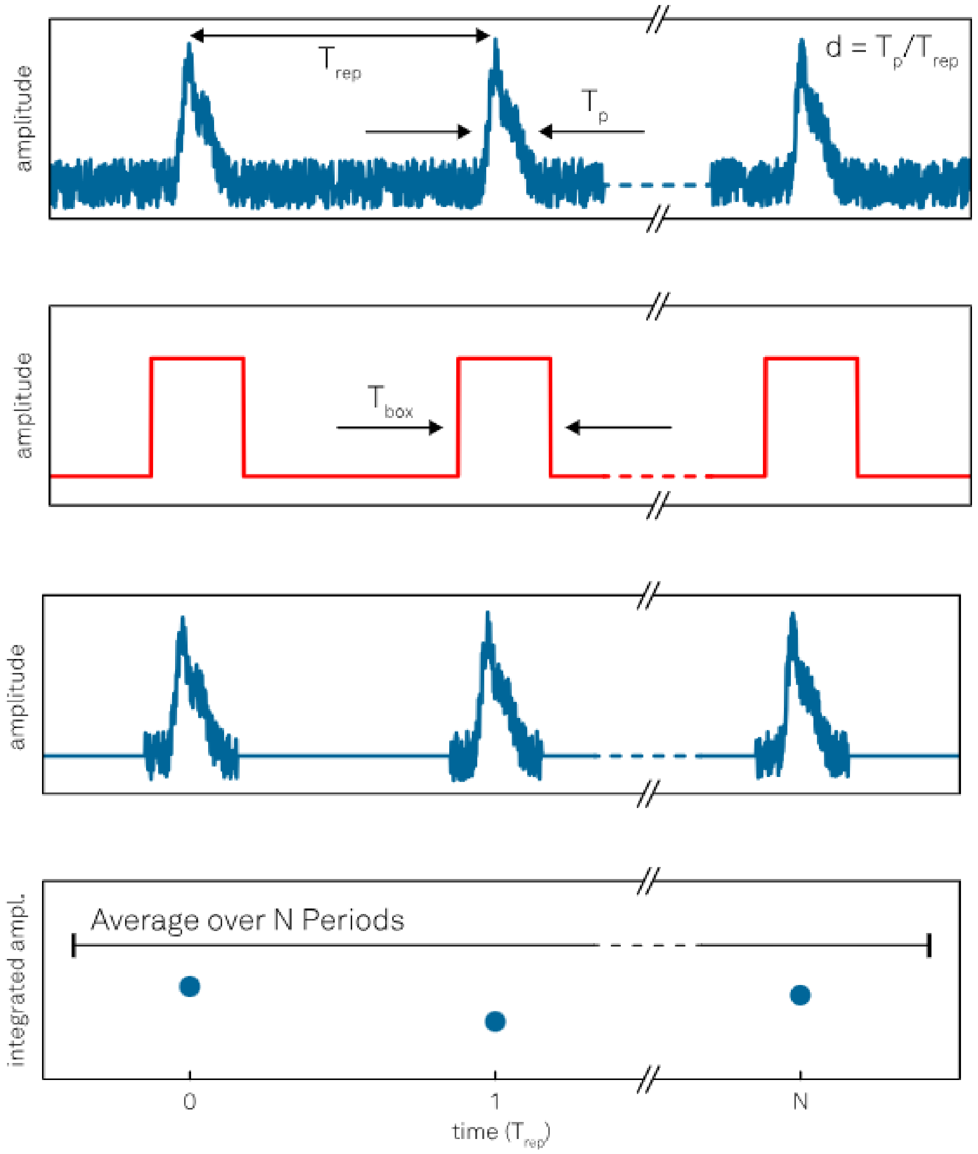

Figure 39. Working principle of a boxcar averager. (Principles of Boxcar Averaging | Zurich Instruments, 2022).

In conclusion, the boxcar averager is a good alternative to the lock-in amplifier for this project, particularly for smoothing out high-frequency noise. It offers simplicity and cost-effectiveness, though it comes with the trade-off of potential resolution loss and lack of frequency specificity. For many applications, especially those where the signal of interest is relatively stable and the noise is high-frequency, a boxcar averager can significantly improve the signal-to-noise ratio effectively.

6.2.2 QUALITATIVE ANALYSIS OF RESULTS

The experimental data collected from the sensor in three different lighting conditions—natural light only, combined natural and artificial light, and artificial light only—revealed distinct voltage outputs at the circuit's output. Specifically, the measured voltages were 264 mV for natural light, 304 mV for combined natural and artificial light, and 272 mV for artificial light.

These results demonstrate the sensor's capability to distinguish between different lighting conditions, with the highest voltage corresponding to the combined light scenario. This indicates the successful implementation of the lock-in amplifier and the overall system's effectiveness in quantifying artificial light even in the presence of natural light.

Furthermore, the output voltages reflect the system's sensitivity to variations in light intensity. The increase in voltage from natural light to combined light highlights the system's ability to detect additional artificial light, while the voltage difference between combined light and artificial light alone suggests the system can isolate and measure artificial light contributions accurately.

In conclusion, by employing synchronous detection, the lock-in amplifier effectively isolates the signal at the modulation frequency, significantly enhancing the signal-to-noise ratio. The subsequent low-pass filter stage further refines this signal by removing high-frequency noise components, allowing only the desired frequency components to pass through. This dual-stage process ensures that the output signal is clean and precise, suitable for accurate measurements and analysis.

7. PRACTICAL APPLICATIONS

In this section, we explore the practical applications of the developed methodology and its potential benefits and limitations in various contexts.

7.1 EXAMPLES OF APPLICATIONS

7.1.1 INDUSTRIAL APPLICATIONS

The methodology presented in this report holds significant relevance in industrial settings where precise measurement and control of light signals are paramount. Industries such as semiconductor manufacturing, telecommunications, and aerospace engineering can leverage the developed system for tasks such as quality control, optical inspection, and signal processing. The ability to discriminate artificial light signals from background noise enables enhanced monitoring and optimization of industrial processes, leading to improved efficiency and productivity.

7.1.2 SCIENTIFIC APPLICATIONS

In scientific research, the capability to accurately measure and analyze light signals has diverse applications across multiple disciplines. For instance, in astronomy, the developed methodology can facilitate the study of celestial objects and phenomena by filtering out interference from ambient light sources. Similarly, in biophotonics and medical imaging, precise light measurement techniques are essential for diagnostics, imaging, and therapeutic interventions. By providing a reliable means of quantifying light signals, the developed system contributes to advancements in scientific research and technological innovation.

7.2 BENEFITS AND LIMITATIONS

7.2.1 COMPARISON WITH OTHER MEASUREMENT METHODS

A comparative analysis of the developed methodology with existing measurement methods reveals several advantages, including high sensitivity, improved signal-to-noise ratio, and reduced susceptibility to environmental interference. Compared to traditional photometric and radiometric techniques, the use of lock-in amplification offers superior performance in discriminating weak light signals from background noise. However, it is essential to acknowledge the limitations of the developed system, such as the requirement for specialized equipment and expertise, as well as potential constraints in dynamic range and measurement accuracy under certain conditions.

7.2.2 POTENTIAL IMPROVEMENTS

While the developed methodology represents a significant advancement in light measurement technology, there are opportunities for further refinement and enhancement. Potential areas for improvement include the optimization of circuit design parameters, the integration of advanced signal processing algorithms, and the exploration of alternative detection technologies. Additionally, ongoing research and development efforts can focus on addressing specific limitations, such as mitigating sources of electromagnetic interference and expanding the applicability of the system to diverse environments and operating conditions.

8. CONCLUSIONS

8.1 SUMMARY OF RESULTS

In this project, it has been successfully reached the goal of developing and implementing a system for converting a periodic light signal into a continuous signal using a photodiode and a lock-in amplifier. The primary objective was to accurately quantify artificial light in the presence of natural light, addressing the challenges of measuring light in various environmental conditions. Our circuit design, which included multiple amplification and filtering stages, effectively enhanced the signal-to-noise ratio, allowing for precise light measurements.

Key results include:

- The effective filtration of continuous components and high-frequency noise, resulting in a clear sinusoidal reference signal.
- The successful amplification of weak light signals while maintaining the integrity of the signal frequency.
- The demonstration that the lock-in amplifier can isolate the desired signal from background noise, enabling accurate measurements during daylight hours.

8.2 ACHIEVEMENTS

The achievements of this project are significant and include:

- Designing a robust PCB that integrates a photodiode and lock-in amplifier, capable of distinguishing artificial light in various lighting conditions.
- Implementing a series of amplification and filtering stages that enhance the signal quality and improve measurement accuracy.
- Validating the system's performance through practical testing, demonstrating its potential for real-world applications in monitoring lighting standards and energy consumption.

8.3 FUTURE RESEARCH DIRECTIONS

While the current system performs well, there are several areas for future research and improvement:

- Optimization of Component Selection: Further research could explore the use of advanced low-noise components to further reduce the baseline noise level and enhance signal clarity.

- Integration with Digital Signal Processing: Incorporating digital signal processing (DSP) techniques could improve the flexibility and accuracy of the system, enabling real-time data analysis and enhanced noise reduction.

- Miniaturization and Portability: Developing a more compact and portable version of the system could facilitate wider adoption and ease of use in various field conditions.

- Extended Testing and Calibration: Conducting extensive testing and calibration in different environmental conditions and with various light sources could help refine the system's performance and reliability.

- Exploration of Alternative Techniques: Investigating other signal processing techniques, such as the boxcar averager, could provide valuable insights and potentially enhance the system's capabilities.

By addressing these areas, future research can build on the foundation laid by this project, leading to even more accurate and versatile light measurement systems.

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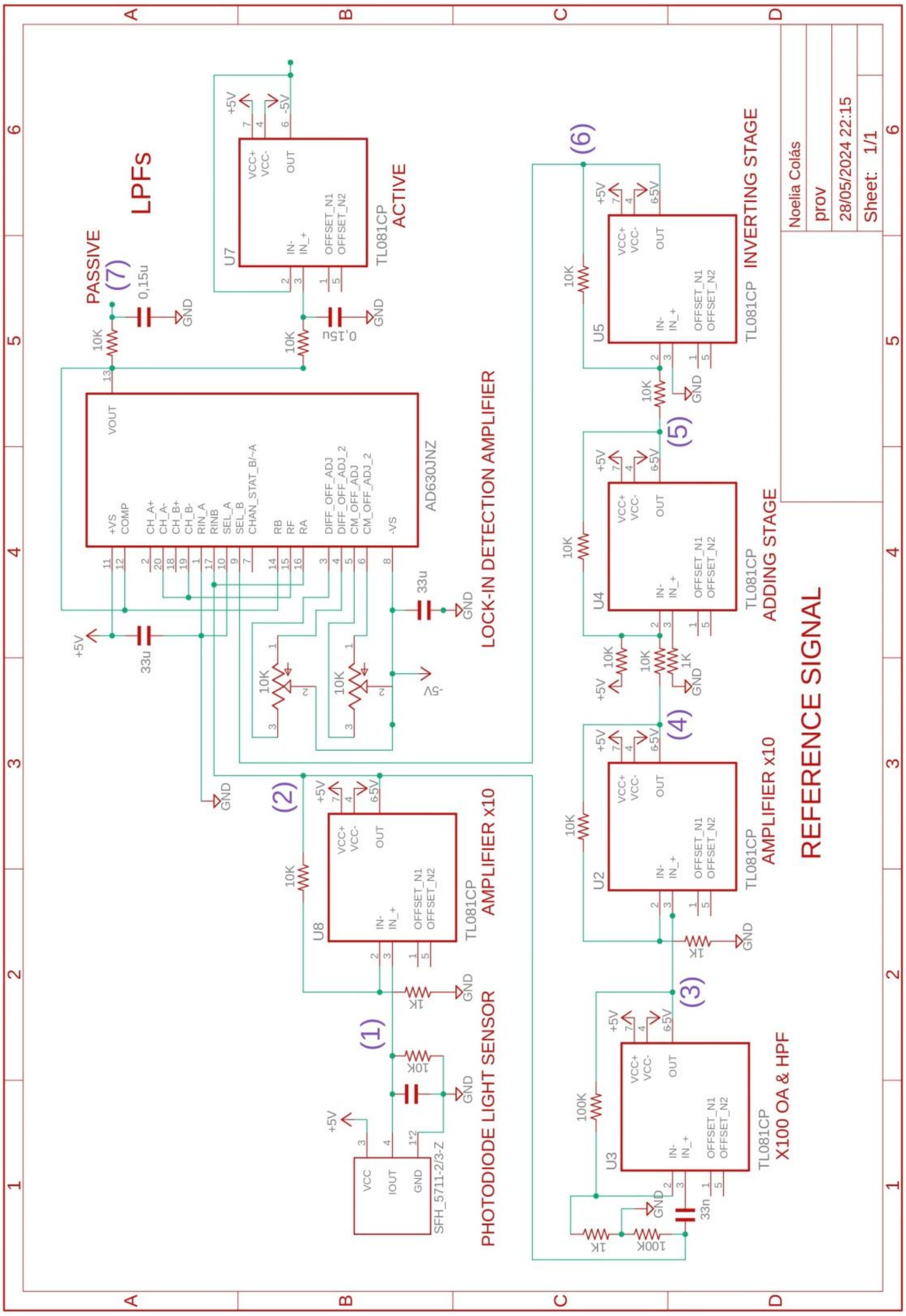
Annex A: Circuit Schematic Diagram

Figure A1. Complete Circuit Schematic Diagram



***Description**:* This figure provides a comprehensive view of the entire circuit used in the light measurement system. The photodiode, lock-in amplifier, and all other components are shown with detailed connections and annotations.

By organizing the content in this way, you ensure that the main body of your document remains concise and readable while still providing all necessary details in the annex. This approach also helps maintain the flow of your report and makes it easy for readers to locate the full schematic when needed.